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MESSAGE FORWARDING TECHNIQUES IN BLUETOOTH ENABLED OPPORTUNISTIC COMMUNICATION ENVIRONMENT

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Submitted in total fulfilment of the requirements of the degree of Doctor of Philosophy

December 2014

Dedicated to

My Loving Family

Acknowledgment

In the name of ALLAH, the most Beneficent, the most Merciful. First and foremost, I am thankful to Allah Almighty for his countless bounties and blessings, who gave me strength, health and determination to write this thesis.

In this very special occasion, I would like to express my deepest gratitude and appreciation to my supervisor Dr. Jonathan Loo for his priceless technical, academic and consistent moral support. His supervision has helped me learn the right way of thinking, tracking problems and overcoming challenges. He supported me throughout the course of my thesis work with his knowledge and patience. Also, I am very grateful to Dr. Aboubaker Lasebae for his support in this endeavour. I would also like to appreciate academic and management stuff in School of Science and Technology at Middlesex University London for providing very good academic and friendly environment.

Also, it won't be justifiable if I do not express my gratitude to all my friends, colleagues and faculty members for their immense support and motivation during the progression of this thesis. I would also like to praise Higher Education commission of Pakistan for the efforts they are putting for the betterment of the education in Pakistan.

In this very special moment, I would like to record my profound appreciation to my parents. Their unconditional love, motivation and faith in me, made me the person I am today. My deepest appreciation goes to my siblings for their never ending encouragement and love.

Last but not the least, my special thanks goes to my dearest and loving wife, for understanding attitude, unconditional love and encouragement especially in difficult situations. Finally, I would like to dedicate my work to my loving family.

Sardar Kashif Ashraf Khan

Abstract

These days, most of the mobile phones are smart enough with computer like intelligence and equipped with multiple communication technologies such as Bluetooth, wireless LAN, GPRS and GSM. Different communication medium on single device have unlocked the new horizon of communication means. Modern mobile phones are not only capable of using traditional way of communication via GSM or GPRS; but, also use wireless LANs using access points where available. Among these communication means, Bluetooth technology is very intriguing and unique in nature. Any two devices equipped with Bluetooth technology can communicate directly due to their unique IDs in the world. This is opposite to GSM or Wireless LAN technology; where devices are dependent on infrastructure of service providers and have to pay for their services. Due to continual advancement in the field of mobile technology, mobile ad-hoc network seems to be more realised than ever using Bluetooth.

In traditional mobile ad-hoc networks (MANETs), before information sharing, devices have partial or full knowledge of routes to the destinations using ad-hoc routing protocols. This kind of communication can only be realised if nodes follow the certain pattern. However, in reality mobile ad-hoc networks are highly unpredictable, any node can join or leave network at any time, thus making them risky for effective communication. This issue is addressed by introducing new breed of ad-hoc networking, known as opportunistic networks. Opportunistic networking is a concept that is evolved from mobile ad-hoc networking. In opportunistic networks nodes have no prior knowledge of routes to intended destinations. Any node in the network can be used as potential forwarder with the exception of taking information one step closer to intended destination. The forwarding decision is based on the information gathered from the source node or encountering node. The opportunistic forwarding can only be achieved if message forwarding is carried out in store and forward fashion. Although, opportunistic networks are more flexible than traditional MANETs, however, due to little insight of network, it poses distinct challenges such as intermittent connectivity, variable delays, short connection duration and dynamic topology. Addressing these challenges in opportunistic network is the basis for developing new and efficient protocols for information sharing.

The aim of this research is to design different routing/forwarding techniques for opportunistic networks to improve the overall message delivery at destinations while keeping the

communication cost very low. Some assumptions are considered to improved directivity of message flow towards intended destinations. These assumptions exploit human social relationships analogies, approximate awareness of the location of nodes in the network and use of hybrid communication by combining several routing concept to gain maximum message directivity.

Enhancement in message forwarding in opportunistic networks can be achieved by targeting key nodes that show high degree of influence, popularity or knowledge inside the network. Based on this observation, this thesis presents an improved version of Lobby Influence (LI) algorithm called as Enhanced Lobby Influence (ELI). In LI, the forwarding decision is based on two important factors, popularity of node and popularity of node's neighbour. The forwarding decision of Enhanced Lobby Influence not only depends on the intermediate node selection criteria as defined in Lobby Influence but also based on the knowledge of previously direct message delivery of intended destination.

An improvement can be observed if nodes are aware of approximate position of intended destinations by some communication means such as GPS, GSM or WLAN access points. With the knowledge of nodes position in the network, high message directivity can be achieved by using simple concepts of direction vectors. Based on this observation, this research presents another new algorithm named as Location-aware opportunistic content forwarding (LOC).

Last but not least, this research presents an orthodox yet unexplored approach for efficient message forwarding in Bluetooth communication environment, named as Hybrid Content Forwarding (HCF). The new approach combines the characteristics of social centrality based forwarding techniques used in opportunistic networks with traditional MANETs protocols used in Bluetooth scatternets.

Simulation results show that a significant increase in delivery radio and cost reduction during content forwarding is observed by deploying these proposed algorithms. Also, comparison with existing technique shows the efficiency of using the new schemes.

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List of Acronyms

AODV	Ad hoc on Demand Distance Vector
AP	Access Point
ACL	Asynchronous Connectionless Links
BR	Bubble Rap
BNEP	Bluetooth Network Encapsulation Protocol
CAR	Context-Aware Routing
DSDV	Destination Sequenced Distance Vector
DTNs	Delay Tolerant Networks
ELI	Enhanced Lobby Influence
EPI	Epidemic
FEC	Forward Error Correction
GPS	Global Position System
GSM	Global System for Mobile Communication
GPRS	General Packet Radio Services
HCF	Hybrid Content Forwarding
HR	High Rank
HS. R	Highest Rank
ID	Identifier/Identification
IRTF	Internet Research Task Force
IEEE	Institute of Electrical and Electronics Engineers
LI	Lobby Influence
LOC	Location-aware Opportunistic Content Forwarding
LMP	Link Management Protocol (LMP),
L2CAP	Logical Link Control and Adaption Protocol
LAN	Local Area Network
LTE	Long Term Evolution

M	Master
MANETs	Mobile ad hoc networks
MAPs	Mobile Access Points
MV	Meeting and Visits
NS-2	Network Simulator 2
ONE	Opportunistic Networking Environment
PSNs	Pocket Switched Networks
PAN	Personal Area Network
PDAs	Personal Digital Assistant
RPs	Rendezvous Points
S	Slave
SWIM	Shared Wireless Infostation Model
SNC	Saami Network Connectivity
SMS	Short Message Service
SMM	Simple Movement Model
TCP/IP	Transmission Control Protocol/Internet Protocol
TTL	Time to Live
UCBT	University of Cincinnati BlueTooth
WDM	Working Day Movement Model
XOR	Exclusive OR

List of Publications

Journal Papers

[1] **S. K. A. Khan**, J. Loo, A. Lasebae, M.A. Azam (2014), “LOC algorithm: Location-aware opportunistic forwarding by using node's approximate location”, in International Journal of Pervasive Computing and Communications, Vol. 10, Issue 4, 2014.

[2] **S. K. A. Khan**, J. Loo, A. Lasebae, M.A. Azam (2014), “Enhanced Lobby Influence: criterion based information forwarding algorithm for opportunistic networks”, submitted for journal publication in International Journal of Pervasive Computing and Communications, Emerald UK.

Conference Papers

[1] **S. K. A. Khan,** J. Loo, M.A. Azam, H. Sardar, & M. Adeel (2013), “*LOC: Location-aware opportunistic content forwarding using direction vectors*”, IEEE Symposium on Computers & Informatics (ISCI 2013), Langkawi, Malaysia, 07-09 April 2013. DOI: 10.1109/ISCI.2013.6612400

[2] **S. K. A. Khan,** J. Loo, M.A. Azam, H. Sardar, M. Adeel & L. N. Tokarchuk (2012), “*Enhanced Lobby Influence: Knowledge based content forwarding algorithm for opportunistic communication networks*”, 20th International Conference on Software, Telecommunications and Computer Networks, SoftCOM 2012.

[3] **S. K. A. Khan,** J. Loo, M.A. Azam, H. Sardar, M. Adeel & L. N. Tokarchuk (2012), “*Hybrid content forwarding technique for Bluetooth communication environment*”, 20th International Conference on Software, Telecommunications and Computer Networks, SoftCOM 2012.

[4] **S. K. A. Khan**, R Mondragon and L. N. Tokarchuk (2012), “*Lobby Influence: Opportunistic forwarding algorithm based on Human social relationship*”, International Workshop on the Impact of Human Mobility in Pervasive Systems and Applications (PerMoby 2012)

Chapter 1

Introduction

This thesis presents experimental studies on novel routing/forwarding techniques in opportunistic networks. This chapter introduces the underlying motivation of this thesis work in the light of the recent development in this area. The key research challenges in opportunistic networks are also highlighted in this chapter followed by the objective and contribution of this thesis.

1.1 Motivation

Unlike traditional networks such as wired networks, opportunistic networks nodes don't have prior knowledge of routes to the destination. In such networks, the challenge is to effectively deliver messages to the destinations while maintaining minimum communication costs. In opportunistic network any node can be utilised to forward information to intended destinations, provided that node can indeed forward information in the direction of destination node. Nodes have to forward messages to the intermediate nodes depending upon the probability of delivering message to its destination; the message may or may not deliver to the destination nodes. The easiest way to solve this issue is to flood messages throughout the network, but this kind of communication is not acceptable since it has degrading effects on network resources. Epidemic algorithm [1] has addressed this issue and reduced the communication cost significantly by not delivering the same packet to the same node twice. Though Epidemic algorithm has managed to reduce the cost, but it still floods the network in control manner.

To reduce the communication cost in the opportunistic networks, many social algorithms [2, 3] have been proposed. These social algorithms are fundamentally based on three centrality measures betweenness [4], degree [5] and closeness [6]. The main concept behind these algorithms is to exploit those nodes which have important significance in the network. The targeting of significant nodes improves the chances of delivering the messages to intended destinations. These important nodes may have the direct knowledge or they may know the other nodes that have knowledge of intended destinations. Based on similar concept, Bubble Rap (BR) [2] proposed the idea of exploiting popular nodes in the network. These popular nodes can act as efficient message forwarders as they have knowledge of many other nodes in the network. Bubble Rap has significantly reduced the communication cost as compare to Epidemic. However, popular nodes have to pay price in the form of quick resource exhaustion.

The BR is the first opportunistic forwarding algorithm that brings the use of social based forwarding techniques in limelight. The idea is simple that content forwarding in opportunistic networks can be incorporated with human social analogies. Based on similar concept, another technique known as diplomat's dilemma [9] is inferred from the analogy of diplomat. A diplomat has ties with influential people in the society, thus targeting these individual gives more knowledge of the society. Based on the concept of diplomat's dilemma, Lobby Index [7] presented by Korn et al, which introduces a Lobby Index metric that defines "*a node has high lobby index if its neighbours have at least equal or more neighbours than the node itself*" [7]. Another socially inspired algorithm is Lobby Influence (LI) [3], which exploits important nodes on the basis of popularity [2] and popularity of node's neighbour [7]. According to LI algorithm, not only popular nodes have significance in the network but also those un-popular nodes which have popular neighbours are significant. LI has not only improved the overall message delivery ratio but also reduced the delays; however, its communication cost is still higher than BR algorithm.

Almost all of these opportunistic algorithms considered one-to-one node communications, where nodes communicate using Bluetooth with only one encountering node at a time. However, one-to-one communication is not the only option; nodes can also communicate using single or multi-hop formation via bridge nodes in Bluetooth communication environment. In Bluetooth, multi-hop communication can be realised by the formation of piconet or scatternets. MANETs protocols such as Adhoc on Demand Distance Vector (AODV) [10] or Destination-Sequenced Distance Vector (DSDV) [11] are used in scatternets for route learning to the intended destinations. In piconet one master and seven slave nodes are allowed, master node has to play an important role as a central entity. In scatternet, more than eight nodes form multiple piconets that communicate each other via bridge node; bridge node has a key responsibility as a communicator among two piconets. Scheduling performance [12, 13] of the master node dictates the efficiency of a piconet. Whereas, not only scheduling performance of master node but also performance of bridge node does play an important role for overall efficiency of scatternet. Several bridge algorithms have been proposed [14, 15] for

Bluetooth nodes acting as a bridge node in scatternet. In [16] Law et al proposed an efficient scatternet formation algorithm to minimise inter-piconet interference and avoid bottlenecks.

This thesis presents analyses with experimental results of different routing/forwarding techniques in opportunistic network using Bluetooth communication. These techniques achieve directivity in opportunistic networks by exploiting human social context, location awareness context and hybrid communication context. In hybrid communication techniques, nodes can adopt either opportunistic forwarding or MANETs techniques as per circumstances of the network.

1.2 Research Challenges

Routing/forwarding in opportunistic networks raise interesting questions compare to the traditional internet communication. Unlike traditional networks, where nodes have prior knowledge of routes to intended destination, in opportunistic networks, nodes don’t have the knowledge in advance. Nodes have very little information based on which they make forwarding decision. Mainly, nodes have to rely on the information they collected earlier or the information shared by the encountering nodes. Therefore, major challenge is finding intended destinations in opportunistic networks.

Another major challenge in opportunistic network is the Cost of communication. In traditional networks, there is a set procedure of finding unknown nodes in the network. However, in case of opportunistic networks, nodes may keep or forward messages to the encountering node based on the ability of finding its intended destination. Simple message broadcasting in opportunistic networks seems the simplest answer but in reality it will increase communication cost immensely. Therefore, message forwarding without generating unwanted traffic is a big challenge in these networks.

In traditional networks, mostly nodes are connected to wire or in case of wireless connectivity they are always in the range of access points. Therefore, very low number of disconnections occurs and the delays are considered minimal, such as in terms of milliseconds, microseconds or seconds. However, opportunistic networks are different breed; any potential node in the network can be used which has ability to find intended destination. For this reason, messages need to be forwarded in store and forward manner, thus causing long variable delays. Designing efficient message forwarding techniques with minimum delays in opportunistic networks is another big challenge.

In recent years, new opportunistic forwarding techniques have been proposed [2, 3], which are inspired from human social context. Social based forwarding algorithms are based on the concept that in networks there are individuals that can play key role in the network to achieve directivity of messages towards intended destinations. These key nodes are selected based on popularity, influence, centrality or betweeness, therefore can be used as efficient message forwarder. Nevertheless, nodes in networks can exploit these key individuals needlessly and may drain their resources very quickly. Therefore, unnecessary exploitation of key individuals in social based forwarding is another challenge.

Another area of opportunistic forwarding technique is based on location awareness of the nodes. In theory, if the location of nodes is known then message directivity can be achieved quite easily. In practice, this theory is not as simple as it seems, first we need to know the location of each individual node in the network by some communication means i.e. GPS (Global positioning system), wireless access point or cell towers. This situation poses some challenges 1) Most of the time nodes are moving, this means continuous update of location for each individual node is required and this information should be available to every other node in the network 2) For continuous update each node should have sufficient battery source to cope with this situation 3) What if some nodes do not have capability of location awareness but are part of the network.

Although, all opportunistic forwarding techniques assumes Bluetooth technology as a communication means among individual nodes in network. This is only acceptable as far as communication is between two individual nodes. However, if single or multi-hop communication is required using Bluetooth technology then concept of piconet or scatternet will be used. In such situation, current opportunistic forwarding techniques will not work. In order to materialise opportunistic forwarding techniques in single or multi-hop Bluetooth environment, opportunistic forwarding techniques need to rely on Bluetooth scatternet formation algorithms as well as traditional ad hoc network protocols such as AODV or DSDV.

In order to study and evaluate algorithms, research community mostly lies on simple proof-of-concept prototypes, simulation and analytical modelling of systems. In modern simulation techniques, researchers evaluate algorithms in synthetic movement models as well as real mobility traces. Selection of appropriate movement model or traces that fulfils the requirement of a particular algorithm is another challenge.

1.3 Research Objectives

The main objective of this research is to design different routing/forwarding techniques in opportunistic networks based on several assumptions to improve directivity of messages towards intended recipients. These assumptions exploit human social relationships analogies, approximate awareness of the location of nodes in the network and use of hybrid communication by combining several routing concept to gain maximum benefit. The aim behind studies of these routing/forwarding techniques is to improve the overall message delivery at destinations while keeping the communication cost very low. In terms of technological aspect, these opportunistic forwarding algorithms are capable to work with any communication technology. However, this research considers Bluetooth as physical communication medium.

1.4 Methodology

The approach that is adapted in this thesis to gauge the performance of proposed algorithms is twofold. The idea is to test these algorithms in two different environments 1) Real mobility traces 2) Synthetic. The real mobility datasets contain the information gathered from experiments performed with real people and devices for certain period of time. The testing of new algorithms in real mobility traces helps us to learn the behaviour of new algorithm in real situations. However, real mobility traces have limitations in terms of resources such as number of nodes, movement models, device life, experiment duration time etc. Therefore, in order to further establish the robustness, the proposed algorithms are further tested in synthetic movement model. In synthetic movement model, there is more flexibility of changing experimental parameters to further gauge the performance of proposed algorithm.

The results gathered from these experiments are drawn in the form of graphs. These results are further compared with the previous state of the art algorithms to gauge the performance of newly proposed algorithms.

1.5 Novelty and Contributions

This research presents several novelties and contributions. The first contribution is an optimized as well as capable knowledge centred information forwarding algorithm named as Enhanced Lobby Influence (ELI), which efficiently progresses whole information delivery along with reduced communication cost. Basically ELI permits nodes to retain information of last recipients to whom they have delivered information directly. ELI mainly gives intelligence to nodes to keep the track of those nodes they met as final recipient in previous course of message delivery. If any intermediate node has previous knowledge of direct delivery to the intended recipient, halts this information forwarding and retains it until deliver directly. As a result a noteworthy volume of traffic is reduced by not permitting to the inappropriate nodes in the network.

Second contribution of this thesis is a location aware content forwarding algorithm using direction vectors, in short "LOC" algorithm. In LOC algorithm, source node is aware of its approximate destination position in the network by the help of GPS. The reference distance and direction values can be calculated from source to intended destinations by using direction vectors. The process of forwarding messages to intermediate nodes is very simple, forward messages to those nodes which have better direction and distance than reference values. By doing this, a great deal of message directivity is achieved.

Last but not least, this thesis presents an approach where an effort is made to combine two different yet related ad-hoc communication approaches such as scatternet formation and social forwarding algorithms. For this purpose, the emphasis of this thesis is to make the routing and content dissemination more efficient by keeping Bluetooth protocol stack and human social relationship patterns in mind. Two well-known algorithms Bubble Rap (BR) [2] and scatternet formation algorithm [16] are combined to form a hybrid content forwarding (HCF) approach.

1.6 Thesis Structure

This thesis is structured as follows:

Chapter 2 gives a review of routing/forwarding techniques in opportunistic networks. This chapter also discusses about key difference between opportunistic and Mobile ad hoc networks. The concept of delay tolerant networking is also discussed here. This review also highlights conditions and features in which opportunistic forwarding can be realised.

Chapter 3 presents a new efficient social forwarding technique known as Enhanced Lobby influence for opportunistic networks. This chapter discusses motivation and background behind development of this algorithm. This chapter also presents experimental results for ELI algorithm. The algorithm presented in this chapter is tested in synthetic movement model as well as real mobility datasets and result comparison is shown.

Chapter 4 presents opportunistic forwarding technique known as Location-aware content forwarding. This technique is based on the approximate location awareness of the nodes in the network. This chapter gives the motivation and background behind this algorithm. This chapter also highlights scenarios in which this algorithm is tested. Finally, gives the experimental results with comparison of LI algorithm.

Chapter 5 presents a proof of concept study by implementing opportunistic algorithm on Bluetooth communication stack. This chapter provides detailed experimental results performed in static and dynamic scatternet environment followed by literature review. Finally, this chapter highlights pro and cons of this study, which paved the way for new hybrid communication algorithm.

Chapter 6 presents a new algorithm known as Hybrid content forwarding. This chapter gives the overview of environment where this algorithm is tested. Finally, gives the experimental results with comparison.

Chapter 7 concludes the thesis work and highlights the future course of direction.

Chapter 2

A Review of Routing/Forwarding Techniques in Opportunistic Networks

Opportunistic networks are designed to operate in challenging environments. Deployment of such networks is typically called for when potential routes from source to destination are unknown. The nodes employed in these networks engage in intermittent connections and the links between them can vary considerably in nature. Intermediate nodes require store-and-forward procedures to negotiate such conditions. Such complexities produce considerable challenges for researchers in the design of novel protocols. This chapter addresses both the fundamental characteristics and the research challenges involved in opportunistic networks.

2.1 Introduction

MANETs (Mobile Ad-hoc Networks) are the focus of considerable current research. The structure-less topology of MANETs enables any node the flexibility to enter and leave a network. However, for functionality an essential prior requirement is knowledge of routing paths. When joining a network, therefore, nodes must first establish destination routes before data can be sent. This is achieved by use of algorithms for ad-hoc routing, such as AODV [10] or DSDV [11].

Opportunistic networks, while notionally operating as MANETs, are a more mobile and flexible concept. In contrast to MANETs, opportunistic networks do not require advance knowledge of routes that connect with destinations. This enables any node on an appropriate path to be opportunistically included in the network as a step toward delivering a message to its destination. Addressing the excessive traffic such message forwarding can generate is one of the biggest challenges faced by researchers in this field.

The rest of this chapter is organized as follows: Section 2 introduces the concept of delay tolerant networks. Section 3 investigates opportunistic networks by surveying some practical uses of this type of network. Section 4 examines state-of-the-art routing and forwarding techniques used in opportunistic networking. Finally, the chapter ends with a summary.

2.2 Delay Tolerant Networks (DTNs)

Delay Tolerant Networks (DTNs) offer a practical advance on several limitations encountered with the traditional internet. The Internet Research Task Force (IRTF) has devoted considerable research into the development of DTNs and has established architecture specifications and definitions for DTNs in different scenarios.

DTNs are networks that are able to operate efficiently in environments where disruption to transmissions commonly occurs. Extreme examples are in space communications, including interplanetary contacts, where the movements of satellites or planets themselves can delay or interrupt transmissions. The solution is to enable data to be stored when communication links are unavailable and transmission to be resumed when the transmission medium is available again. Although a similar process is available in internet and telecommunication networks, using email and SMS, the capacity to manage delays in these networks is necessarily limited.

The significance of the advantages of DTNs initially appeared in the military environment, in which effective battlefield communications are crucially important. The typical movement of soldiers in close formations, despite otherwise hostile locations, offers an appropriate situation for the application of DTNs. Figure 2.1 represents a battlefield in which an ad-hoc communications network enables soldiers to exchange information. Transfer of information to a distant command centre is via a relay node, in this case, on board a helicopter.

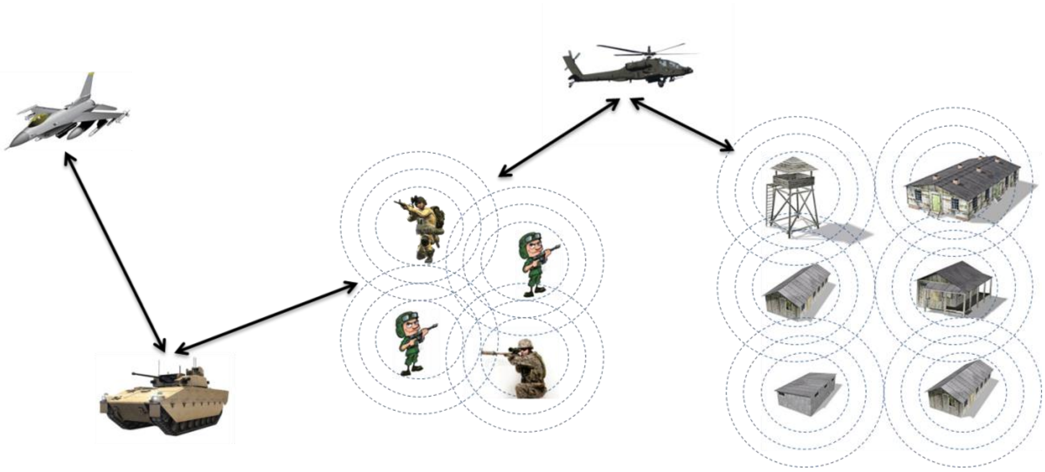


Figure 2.1 MANETs communication

Section 2.2.1 highlights the key characteristics of DTNs, which make them advantageous in many situations when compared to traditional counterparts, such as the internet. Section 2.2.2 describes the typical network architecture of DTNs. Section 2.2.3 explains the key concept of message forwarding in DTNs. And Sections 2.2.4 and 2.2.5, respectively, introduce the typical protocol architecture of DTNs, and the basic role of the node in DTNs.

2.2.1 Why DTNs?

The nature of many recently developed or proposed networks makes them distinct from the conventional definition of the internet. DTNs possess unique characteristics that make them more advantageous and practical than the internet in many situations, as indicated below.

Discontinuous Connectivity: In an environment in which there is a likelihood of encountering broken links the successful use of internet protocols is discounted. DTNs offer a solution to intermittent connectivity between source and destination with use of the store-and-forward messaging concept. DTNs can store messages when links are not available and resume delivery when links are restored.

Unpredictable Delays: Traditional protocols, such as TCP/IP, are capable of managing some communication delays before transmission, but are unsatisfactory if these extend beyond a fixed period. In such cases, a protocol is needed that can handle lengthy or unpredictable delays. DTNs can retain messages for longer periods before transmission; and they are also able to choose an alternative path to reach a destination.

Variation in Data Rates: DTNs can overcome the problem of inconsistent rates of data transmission, which can defeat internet protocols, by resizing the data packets sent. Large packets can be divided up into smaller packets, and vice versa, according to data rate conditions.

Packet Loss: If packet data is lost, or dropped, during transmission, traditional protocols like TCP/IP require full end-to-end retransmission, producing higher data error rates. DTN protocols enable retransmission to occur at point of failure, on a node-to-node basis, thus reducing network overhead time and cost.

2.2.2 Typical Architecture

The architecture of DTNs [21] comprises several (at least two) ad hoc networks in combination. Each participating network becomes an independent DTN region using internet-like connectivity within its boundaries. The communication technology, physical infrastructure and operating protocol within each region remains independent.

Communication between the DTN regions is enabled by DTN gateways, which convert between differing protocols and also protect individual regions from the impact of disconnections. DTNs achieve interoperability across differing regions by introducing a protocol layer, called the bundle layer, which operates above the normal protocol layers of each region.

This concept is illustrated in Figure 2.2, in which DTN gateways manage interconnections between regions that potentially operate different protocol stacks. Region A consists of a mesh network where nodes transfer data and also act as data relays for other nodes. The connection route between Region A and Region C is via satellite. The DTN gateway isolates Region A from any disruptions in satellite communication. Region B covers a wildlife monitoring project. Data is gathered on the movements of animals using an ad hoc network, which involves uniquely tagged antennas on each study animal. The data is sent for store to a remote research site, which also acts a DTN gateway, then taken by researchers to a further research centre at Region C.

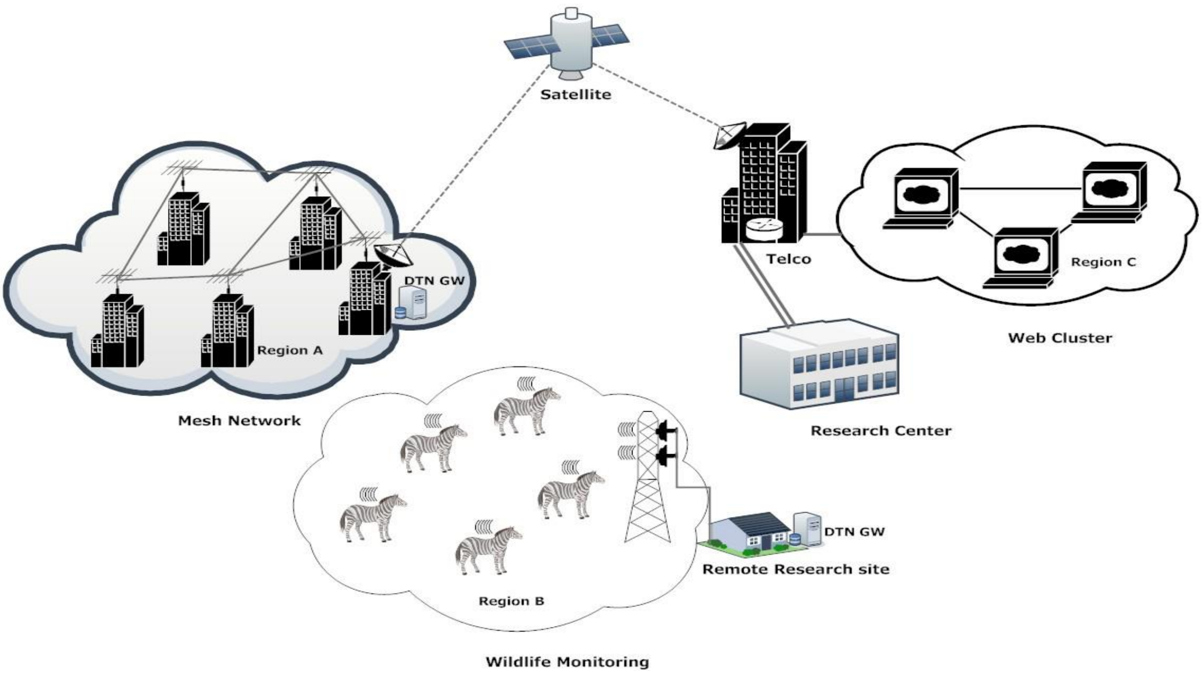


Figure 2.2 Various DTN architecture [89]

2.2.3 Key Concepts of DTNs

Store-and-forward message switching [22] is a key method used by DTNs to overcome several connectivity problems found with traditional internet protocols. Broken links, intermittent connections, uncertain delays, variable data rates and lost data errors are addressed by changing forward transmission procedures. Store-and-forwarding is a concept best illustrated by the mundane postal delivery system, in which letters are stored, sorted and forwarded via consecutive local post offices until they reach their destinations. Limited store-and-forwarding is also applied in email, SMS and voicemail transmissions. In DTNs, nodes along the transmission path have responsibility to transfer data, from node to node, as well as the capacity to store, and possibly re-route, data to best manage current connectivity conditions. Figure 2.3 shows this concept.

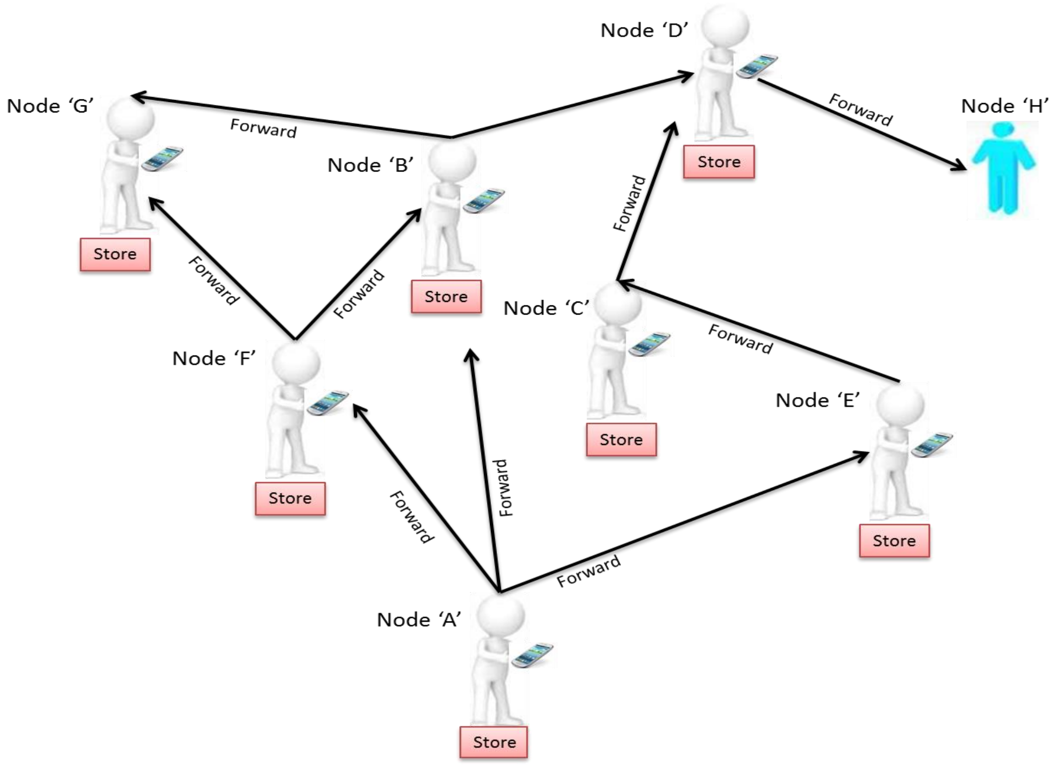


Figure 2.3 Message forwarding in DTNs

Nodes in DTNs can also act as routers. In this environment, routers require continual storage space in order to manage possible data queues. This storage space is required for the following reasons:

- When data path links are broken or unavailable for a long time the responsible node must retain the data until approval for retransmission is received.
- If an error event occurs while transmitting data from node A to node B, node A must keep the data in storage until a successful retransmission is made.

- Variable bandwidth encountered on different nodes on the transmission path means nodes must have the ability to store data in order to negotiate lower bandwidths.

2.2.4 The DTN Protocol Layer

In order to operate across independent regions, DTNs introduce an additional protocol layer that lies on top of conventional internet protocol layers. This layer is called the 'bundle layer' and is able to provide the necessary store-and-forward abilities for operation. In Fig 2.4, the DTN protocol (bundle) layer is shown sitting above TCP/IP architecture. The storing and forwarding of messages (bundles) occurs at this bundle layer, which is the layer responsible for communicating between the participating regions. The layers shown at lower levels on the diagram remain specific to each region, and function independently.

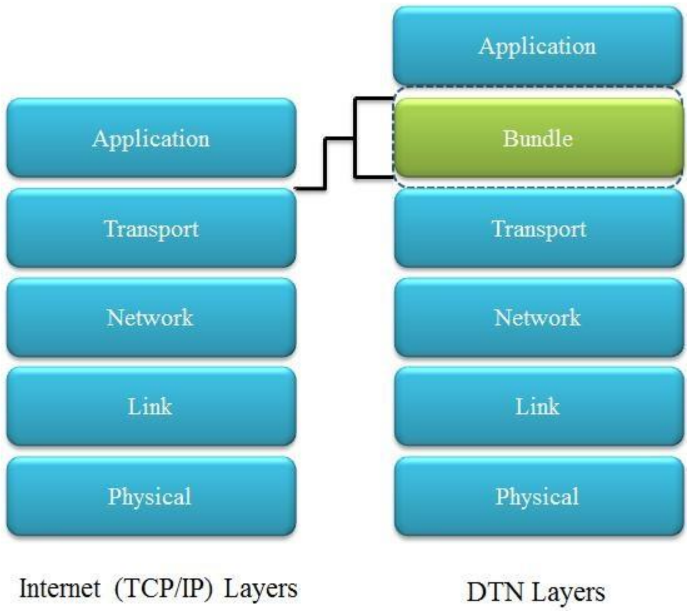


Figure 2.4 DTN protocol stack [89]

2.2.5 Basic Role of a Node in DTNs

At the bundle layer in DTNs, nodes can perform different functions: acting as a message source, destination or intermediate relay (forwarder). The name assigned to a node will depend on its current role in the network. In DTN terminology, this will be either a Host, a Router or a Gateway.

Host: A host may be the source or the destination of bundles (messages) being transferred. Hosts do not act as a relay. A host must have high storage capacity in order to manage any delays in connectivity. Once any unavailable link is restored, message transfer to or from a router can be resumed.

Router: Within each DTN region, a router performs as a relay to achieve transfer of messages from source to destination. In DTNs, nodes may act as routers, as normal receive and forward points, or as both. Nodes acting as routers need storage capacity to manage any unavailability of links. Routing nodes can also be nominated as retransmission points, using a secure procedure known as custody transfer.

Gateway: A DTN gateway functions in a similar manner to that of a router. However, its purpose is to transfer message bundles across the boundary between two different regions in the DTN network.

2.3 Opportunistic Networks

Opportunistic networks and delay tolerant networks are often categorised together, but significant differences between these types of network make opportunistic networks a far more flexible option.

Although addressing several limitations, DTNs remain dependent on internet-like topologies to complete end-to-end data transfers across different regions. This means that links between gateways need to be permanent, nodes are restricted to communicating with a particular gateway, and prior knowledge of network routes from source to destination is required.

Opportunistic networks, in contrast, do not require prior knowledge of network topology. In such ad hoc networks, nodes rely on local routing tables or information from neighbours (closely encountered nodes) to calculate routes to destinations. Each node can act as a gateway, and retain data, until opportunistically encountering another node with the potential to deliver a message directly, or take it one step closer to delivery. The freedom given by the ability to choose any node as a potential relay makes opportunistic networks highly flexible compared with DTNs.

Figure 2.5 shows an opportunistic network where source (left) and destination (right) communicate opportunistically with each other through a number of participating nodes, such as bus, car, child, motorcycle, etc. Any node can be used as a potential candidate for message transfer.

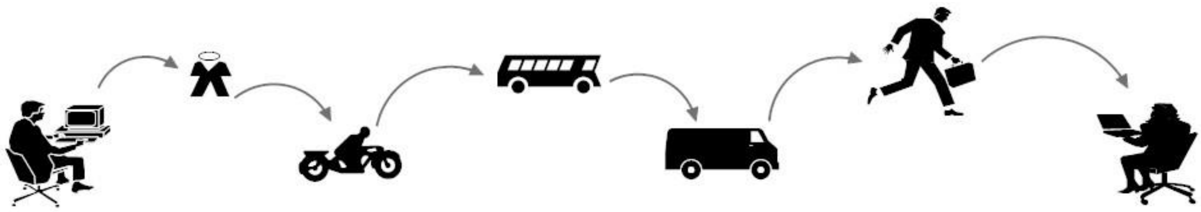


Figure 2.5 Opportunistic communication [89]

Pocket Switched Networks (PSNs), employing devices such as mobile phones and PDAs, can be used to create a specialised form of opportunistic communication network. A mobile phone using Bluetooth technology can transmit messages to other mobile phones, or store messages until it makes contact either with the intended destination or another PSN device acting as a forwarding node to the destination.

The next section examines three popular application domains of opportunistic networks. Section 2.3.1 discusses a number of projects conducted to gather real life mobility traces for learning purposes. Section 2.3.2 highlights projects using opportunistic networks for wildlife studies. And Section 2.3.3 describes the practical implementation of opportunistic networks in rural areas.

2.3.1 Human Mobility Case Studies

Opportunistic networks require a different approach to the design of new protocols than traditional internet networks. As the active nodes in such networks do not have prior routing knowledge they are dependent only on local information and that from encountered nodes. The uncertainty of discovery implicit in such networks has prompted researchers to undertake real world experiments to increase understanding of actual behaviours. These experiments have produced greater knowledge of node behaviour, especially in relation to contact frequency, time, duration, proximity, etc. The data gathered from these experiments has been made freely available to enable others to conduct further beneficial research and development. This type of information, known as 'real world mobility traces', can significantly assist in designing new and more efficient protocols. The following are two examples of such experiments:

The Reality Mining Project: The Reality Mining Project, organised by MIT Media Lab [18], involved experiments designed to collect real time data relating to human social behaviours. The resulting data collection, including insights into conversation contexts, proximity sensing and temporospatial locations, has significantly helped expand modelling concepts of individuals in society.

The reality mining experiment involved use of adapted mobile phones, issued to one hundred college-based participants, to capture data on individual and group daily activities, communications, locations and proximities over the course of an academic year. The project gathered about 350,000 hours of continuous human behaviour data: equivalent to approximately 40 man years. The resulting data set from the Reality Mining Project, issued by MIT Media Lab, has since been widely used in studies of human behaviours [18, 24].

The Haggle Project: The Haggle Project [25], funded by the European Commission, has conducted many experiments aimed at the development of opportunistic networks. The project is specifically focused on protocols for Pocket Switched Networks (PSNs), under the framework defined in [26], in which candidate mobile phones and PDAs may be used as communication nodes for performing opportunistic message transfers. The main objective is to exploit paired [23] opportunistic contacts in device-to-device and user-to-device communication.

Pair-wise contacts are described by *contact duration* and *inter-contact time*, with these two parameters defined as follows:

- When two mobile nodes become close, with the opportunity to communicate with each other, time spent within each other's scope is known as contact duration.
- When two mobile nodes have made previous contact and make contact again, the time spent with each other is known as inter-contact time.

In the Haggle Project experiments, various mobile phones and PDAs were deployed in the field to collect real world data. The information provided by these real world traces has created considerable advancements in knowledge, enabling researchers and students to use these traces for further developmental study of mobile opportunistic networks.

2.3.2 Wildlife Monitoring

The monitoring of wildlife populations is a productive area for the deployment of opportunistic networks. Such networks can help biologists study animal life cycles, relationships with other animals, and the effects of ecosystems on animal behaviour. This kind of wildlife monitoring generally involves wireless sensor tags with storage capacity attached to target animals. The tags collect information, the data is sent to a base station, and it is then forwarded to a processing centre.

Gathering information in such networks is challenging as a base station cannot be deployed for each animal; thus there is a dependence on opportunistic networks. In this context, it is the tags attached to animals that form the opportunistic network. Using a store-and-forward mechanism, information can be transferred from one animal to another until the collected data reaches the base station.

Some of the well-known networked wildlife projects are discussed below:

ZebraNet: A Princeton University project known as ZebraNet [27, 28] monitored the activities of zebras in their natural environment. The project was deployed in the Savanna area of central Kenya, where selected zebras were equipped with sensor collars monitored by researchers from a vehicle-based base station. Information from the collars could be collected as the vehicle encountered animals as it circulated in the Savanna Wild Park.

Three algorithms for data transfer were tested in ZebraNet: *direct, flooding* and *history-based*. In the direct protocol, each collar had to deliver data directly to the base station. In flooding, data was transferred in a broadcast manner, with each collar (node) transferring data successively to the collar of any participating animal encountered, until data reached its destination. Simulation results showed that the flooding protocol performed exceptionally well compared to the direct protocol.

The history-based protocol involved selection of a potential data transfer partner, based on the highest number of meeting-counters with the base station neighbouring collars had achieved. Meeting-counters increased every time a collar encountered the base station, and decreased if the collar had not encountered the base station for a period of time. Simulation results showed that the history-based protocol was better than the flooding protocol, not only in terms of efficient information transfer, but also in saving bandwidth and energy.

Shared Wireless Infostation Model (SWIM): In the SWIM project [30], an opportunistic network was introduced to monitor the behaviour of whales. Each whale in the project had a sensor tag attached to it. Information from each whale was transferred from tag to tag (whale to whale) until reaching the SWIM station research centre for further processing. The concept approach employed in the SWIM project is similar to that used in ZebraNet [29].

2.3.3 Internet for Rural Areas

DakNet Project: The DakNet Project [31] has been deployed in India and elsewhere, with the aim of providing rural areas with intermittent network-based internet facilities where lack of telecommunication infrastructure means standard internet-like technologies are not available.

Individual networks involve the use of village-based kiosks equipped with short range wireless connectivity and capable of storing electronic data. Data inputted at the kiosk can be uploaded to any dedicated vehicle mounted with Mobile Access Points (MAPs). When such MAP vehicles then travel to a nearby town the data is uploaded to the internet. The same process can be operated in reverse, with MAPs downloading internet data in a nearby town and downloading it again to the village kiosks. Networks of this kind are low cost and can provide a variety of services such as, email exchange, audio/video messaging, mobile e-commerce, voting, managing health records and delivering environmental sensor information.

Saami Network: The Saami Network Connectivity (SNC) Project [32] has used a similar concept to DakNet to provide intermittent internet connectivity to the Saami population, who live in the remote north of Sweden.

2.4 Routing/Forwarding Techniques

Opportunistic networking can be classified into two broad categories: *infrastructure-based* routing and *infrastructure-less* routing. When considering new techniques for forwarding/routing the aim is not only to seek a guarantee of message delivery but also to address issues of reducing the time delay and communication cost involved in transferring messages from source to destination. Before discussing different routing techniques in opportunistic networks, Section 2.4.1 provides a brief introduction to the parameters used to gauge the performance of opportunistic forwarding algorithms.

2.4.1 Parameters

The following parameters represent the main considerations when gauging the efficiency of any routing/forwarding technique:

Delivery ratio: Equation 2.1 gives the general expression of delivery ratio used to check the average efficiency of message delivery from source to destination.

$$Delivery\,ratio = \frac{T_{re}}{T_{tr}} \tag{2.1}$$

Where; T_{re} is total average amount of data received at all destinations and $T_{tr}$is total average amount of data send by all sources.

Delay: Another parameter to check the overall delay experienced by messages from sources to destinations. An expression for the delay check can be derived from equation 2.1:

$$Time\ Delay = T_{re} - T_{tr} \tag{2.2}$$

Where; T_{re}time at which data is received at destination and T_{tr}time when message is sent by source.

Communication Cost: The total number of messages forwarded and reaching their destinations defines the overall cost of the network, which ultimately affects utilization of system resources (bandwidth and energy).

These three parameters – delivery ratio, time delay and communication cost – are thus the main challenges facing researchers when proposing and designing new routing/forwarding techniques for opportunistic networks.

2.4.2 Infrastructure-Based Routing

Infrastructure-based routing can be deployed in a network in a variety of ways. This section discusses the core methods:

Node-to-Base Station Communication Only: Infrastructure-based routing is defined by the presence of static nodes, or base stations, which are sparsely deployed through the network. In node-to-base station communication, these static nodes (base stations) take the role of accepting messages directly from the source node and delivering directly to the destination node. As the static nodes, by definition, are fixed in location, source nodes must carry the message, stored in a database, until within range of the static node. At this point, message transfer can occur from source node to static node. Similarly, the static node stores the message until the destination node comes within its range when the message can be delivered to its destination. In this type of network, only source node-to-static node and static node-to-destination node communication is possible. Examples of this type of message routing are *infostations* [33], which act as static base stations deploying high data-rate wireless communication equipment and delivering web services to users that come within range.

Node-to-Node and Node-to-Base Station Communication: This type of network allows a node to transfer messages directly to a base station. To increase flexibility, nodes can also transfer to another node, or several nodes as a relay, in order to reach the base station if it is not immediately within reach. This type of deployment allows only node-to-node and node-to-base station message transfer. The drawback of this arrangement is that it is energy inefficient, despite being able to minimise delays. The ZebraNet [27] and SWIM [30] projects, discussed earlier, are examples of this type of network.

Mobile Infrastructure-Based Routing (Carrier-Based Routing): Carrier-based routing employs mobile nodes, which are added into the network and collect information from other nodes. These nodes may follow either pre-determined or ad hoc routes in the network, in which they collect (or deliver) messages from (or to) nodes they encounter. Such mobile nodes may be variously named as carriers, supports, forwarders, MULEs or ferries. Carrier-based routing may allow only node-to-carrier message transfer, in which case the mobile carrier nodes are responsible for delivering messages to destination. This configuration is very energy saving but can result in added delay. If nodes are only sparsely located in the network, then node-to-node communication may be additionally required. This latter arrangement improves delivery efficiency but increases energy cost.

Data-MULE Systems [34]**:** Data-MULE systems employ the combination of wireless sensors, deployed in a local network gathering information, and a mobile MULE (or carrier) that can receive information from the sensors. The objective is to maximise energy efficiency. When the mobile MULE passes close to a sensor, sensor-to-MULE communication occurs and information is uploaded to the MULE. Subsequently, when the MULE is within range of an Access Point (AP), the collected information can be downloaded to the AP. APs are themselves connected to a data center where received data can be stored for later processing.

Message Ferrying Approach [35]**:** Message ferrying involves the introduction into a network of additional mobile nodes, known as message ferries, which perform the role of receiving information from the source node. There are two types of communication that can be initiated by this approach:

- **Node Initiated Message Ferrying:** Message ferries in a network move in a pre-determined fixed path, which enables knowledge of their location to all nodes in the network. When a source node needs to transmit information it will initiate a communication, move near to a ferrying node, and transmit its message to the ferrying node.

- **Ferry Initiated Message Ferrying:** If a source node wishes to communicate with a ferry node moving on its default path, it will initiate a request with the assistance of other neighboring nodes if the ferry node is distant. When the request is received, the ferry node will move closer to the source node to accept message transfer.

2.4.3 Infrastructure-less Routing

Routing techniques in infrastructure-less opportunistic networks use broadcasting as the distribution method. Since nodes in opportunistic networks have no prior knowledge of destination routes, this fact can be overcome by broadcasting messages widely from a source node until they are received by their intended destination. This routing method can be successful in a densely populated node network. However, the limitations of this approach are that it is resource intensive. Although the delivery process is fast, the imposition of high network traffic through broadcasting impacts negatively on bandwidth and energy consumption. Such congestion can be reduced by limiting the broadcast message to a certain number of hops, or restricting the number of parallel copy messages. Some of the most well-known opportunistic algorithms for this process are discussed below:

Epidemic Routing Protocol: [1] In epidemic routing a message is distributed across a network through opportunistic pair-wise contacts between nodes. In this sense, it is similar to a virus or disease spread through individual contact. A node is regarded as infected when it acts as the message source node; relay nodes becomes infected when receiving the message through pair-wise contact. An infected node carries the message in its local database until it can be forwarded to a relay node or passed directly to the destination. Nodes that have not received the message are considered susceptible nodes. Nodes that have received the message are considered immune after forwarding the message to another node or to the destination. Potential network congestion is avoided by limiting the number of hop counts between nodes the message can make. When the hop count falls to one, the message can only be delivered directly to the destination.

MV Routing Protocol: The Meeting and Visits (MV) protocol [36] could be described as a more refined approach to epidemic routing. Message transfer between nodes occurs through pair-wise contacts, but rather than contact meetings being random, a choice of forwarding node is made according to potential to reach the destination. This potential is determined by examining a node's recent activity history. The node that has made the most frequent visits to the destination node will be chosen as a potential candidate and selected as a relay to deliver a message to the destination. A similar concept is used in the PROPHET algorithm [37].

PROPHET Algorithm: [37] is a probabilistic routing protocol. The objective is to determine the probability of a node delivering a message to the destination. To achieve this PROPHET employs a probabilistic metric. The meeting of two nodes results in an exchange of delivery predictability vectors. Two nodes which regularly encounter each other will produce a high predictability of message delivery between each other. In contrast, two nodes that do not meet regularly, or have not met for some time, will acquire a low and progressively decreasing delivery predictability metric. Tests of the use of this algorithm to select message delivery nodes showed a significant reduction in communication overheads when compared with epidemic routing [1].

Network-coding-based algorithm: [38, 39] reduces significant amount of network traffic by using a coding mechanism. Suppose two nodes want to exchange data with each other and both nodes use the same middle node as a rely to reach each other. The middle node will gather the information of the two nodes and apply an exclusive OR (XOR) operation on data received from both nodes and broadcast the new XORed data to both nodes. The receiving node can reverse the process and extract its respective information. In this way 50 % of traffic on network can be minimized.

CORE: [40] is another coding-aware routing protocol. The priority given to forwarding nodes in a routing table varies dynamically depending on the coding opportunities. A node has more coding opportunities when it holds more coded packets. To reduce communication costs, the forwarding node must also be the neighbour of the source node and, at the same time, closer to the destination node than the source node.

Context-Aware Routing (CAR) Protocol: In [41], network routing paths are determined by multi-attribute utility theory, in which prior knowledge of each node's individual context is required. This protocol depends on every node in the network possessing a routing table that records the potential of neighbouring nodes to become message forwarders capable of delivering messages to the destination node. Potential forwarders are selected on the basis of such utility factors as battery life, dis/connection rate, mobility pattern and potential for reaching the destination. CAR thus provides a utility framework for selecting potential carrier nodes in opportunistic networks.

MobySpace Routing: [42] is based on context-based routing, where mobility patterns of nodes are used as context information for creating routing paths. The protocol involves construction of a high-dimensional Euclidean space, named MobySpace, in which the axis represents the connection between two nodes and the distance along the axis represents the probability of connection.

Contention-Based Geographic Forwarding: [43] is a geographical information-based routing protocol. In geographical-based protocols it is necessary for each node within the network to have knowledge of its location and that of neighbouring nodes. To achieve this knowledge framework, every node sends a one-hop beacon message to establish co-ordinates from the surrounding nodes. Each node then maintains a location-based table. In [43], the source node initially sends a control packet to its surrounding nodes. Nodes receiving the control packet use their location tables to compare their distance to the intended destination in order to calculate their suitability as message forwarders. This process may involve competitive contention for selection between nodes that are closest to the intended destination. To reduce communication costs, only one node is allowed to become a message forwarder. Once this message forwarder has been determined, the source node transmits its actual message directly to the selected node for onward transmission. This geographically-based selection process can result in increased computation cost due to the election procedure in selecting the message forwarder.

Location-Aided Opportunistic Routing: [44] selects potential forwarding nodes based on a higher packet advancement metric. Packet advancement is the distance between source node and destination node, subtracting the potential forwarding node and the destination node. This metric calculates progress in distance when the forwarding node transmits packets to the destination node. Mathematically [44],

$$D_{ir} = Dist(N_i, N_d) - Dist(N_r, N_d) \tag{2.3}$$

Where; N_i is the source node, N_r is the forwarding node and N_d is the destination node.

To add the potential message forwarder into the forwarding list, the packet advancement metric of potential forwarder is compared to the highest packet advancement metric of all the neighbouring nodes of source node and must be less than predefined threshold value. This process allows nodes to include or exclude new potential forwarders.

Robust Geographic Routing: [45] uses a similar concept to that proposed in [44] by exploiting potential forwarders that are geographically located closest to the destination. This relies on nodes knowing their current position and that of their direct neighbours. Prior to actual message data transmission the source acquires the location of the destination and appends this to the packet header together with its own location. Collecting the necessary information for the process is achieved with use of a one-hop beacon or by piggy-backing in the data's header packet.

Bubble Rap Algorithm: In [2], Hui et al. introduced a social forwarding algorithm, for implementation in Pocket Switched Networks (PSNs), that is based on human mobility traces in social community structures.

This algorithm is called Bubble Rap (BR) and is concerned with two aspects of a society: *community* and *centrality*. The principle follows the observation that human society naturally forms itself into communities. In turn, certain people within those communities become more well-known, or famous, than others. This fame is structured as high centrality and is consequent on such individuals having wider relationships than others. The Bubble Rap forwarding algorithm exploits such popularities of people in society; noting that individuals fulfil different roles and thus have varying popularity levels.

In BR, node popularity is calculated by noting the average contact count over a previous course of encounters with other nodes, using *betweeness centrality*. Betweeness centrality defines the number of times a node participates in message forwarding between source and destination. In PSNs, communication cost can be reduced by allowing popular nodes to act as message forwarder while also improving probability of message delivery to the intended destinations. The forwarding strategy of a message in the BR algorithm is based on the following objectives:

- Locate nodes that are more popular than the current node and forward messages to the newly located nodes.
- Identify nodes belonging (or that can take one step closer) to the target communities and use them as relays.

The algorithm itself is based on the following two assumptions:

- Each node must be assigned to at least one community and nodes may only belong to one community.
- Each node has both global and local ranking. Global ranking identifies a node’s popularity (centrality) across the whole graph. Local ranking identifies a node’s popularity across the local community (sub-graph). If a node is a member of multiple

communities it has multiple local rankings.

The authors proposed three alternative algorithms as part of BR for the detection of communities, namely SIMPLE, K-CLIQUE and MODULARITY. As a result of experimentation, they concluded that K-CLIQUE had 85% accuracy.

The authors also initially proposed that centrality measured historically could be taken as a future centrality predictor. This was gauged by selecting the degree average in unit times throughout experiments, referred to as the *degree* of a node, which represents a node's global and local centrality values. However, experiments proved that total degree (unique nodes seen by a node throughout experiments) was not a good approximator for measuring node centrality.

Therefore, two types of window are recommended: Single (S)-Window and Cumulative (C)-Window, which calculate degree in per unit time. S-Window compares the number of unique nodes found by comparison with a previous unit time slot (i.e., 6 hours recommended). C-Windows takes the average of all previous unit time windows (i.e., 6 hours). Between the two techniques, the authors found C-Windows proved the most efficient

The Bubble Rap algorithm appears to be a practical implementation for PSNs. The BR message forwarding method effectively directs traffic towards intended destinations while reducing redundant traffic in the network. However, BR also presents problems. By focusing on popular nodes in the network, it increases the load on these nodes, potentially causing their buffer to quickly overflow and forcing such nodes to disappear from the network. Furthermore, although the authors have anticipated BR working for hierarchical structures, it has been tested only for flat community structures.

Human Mobility Predictability: In [24], Hui presented an algorithm that can improve forwarding efficiency in terms of delivery ratio and delivery cost by predicting human mobility patterns in day-to-day base. The experimental data set used for this algorithm test is taken from the Reality Mining Project. The algorithm uses vertex similarity to measure the predictability of human interactions and for this purpose classic Jaccard measurement is considered for vertex similarity. The idea is simple: compare the vertex similarity of contact graphs over two days and extract the human interaction similarity. The results presented by this work are based on Jaccard measurement and mathematically the equation is given as [24]:

$$\sigma_{Jaccard} = \frac{|\,\Gamma_i \cap \Gamma_j\,|}{|\,\Gamma_i \cup \Gamma_j|} \tag{2.4}$$

Where; Γ_i is the neighbourhood of vertex i, which is connected to set of vertices connected to vertex i via an edge. $|\Gamma_i|$ is the cardinality of set Γ_i, that is equal to the degree of the vertex i.

SimBet: In [85], the process of selecting forwarding nodes is determined by two attributes: *similarity utility* and *betweeness utility*. The multiple attributes presented by nodes may cause decision problems when selecting the best message forward carrier. This difficulty is answered by making a pair-wise comparison on the normalised relative weights of the attributes. Mathematically [83]:

$$SimBetUtil_n(d) = \alpha \frac{Sim_n(d)}{Sim_n(d) + Sim_m(d)} + \beta \frac{Bet_n}{Bet_n + Bet_m} \tag{2.5}$$

Where; *Sim* is *similarity utility* and *Bet* is *betweenness utility*; *d* is destination node; α and β are tuneable parameters and $\alpha + \beta = 1$; SimBet utility has value between 0 and 1.

PleRank: In [86], the approach used is derived from the concept known as PageRank [85], which was created for the Google search engine to select the relative importance ranking of web pages within the web. PeopleRank proposes a similar technique to rank the relative importance of nodes. Nodes determined with a higher PeopleRank are considered to be more socially active and thus likely to be connected to other important nodes of the network. A significant reduction in communication cost may be achieved by targeting the higher ranking PeopleRank nodes that play an active role in opportunistic networks.

The Diplomat's Dilemma: In [9], the authors place emphasis on the position and influence of the node in the network. Their analysis relies on the social paradigm known as the Diplomat's Dilemma, which implies that professional people (such as diplomats) need to maintain power or a position of influence in society, while expending minimum effort in so doing. The theory suggests such influence can be won by creating relationships with many people, but to maximise efficiency this needs to be achieved with minimum personal contact (i.e. more power /less connections /lower cost).

In this paper, an agent has the power to take strategic decisions in a society. Optimising score functions is achieved by the agent adopting different strategies described by six factors, i.e., MAXD, MIND, MAXC, MINC, RND and NO. These factors define the manner in which an agent's relationships with others are selected within a first degree network neighbourhood. An increase in score function indicates a resulting increase of that agent's influence in the society. A negative impact of this approach in opportunistic networks is the possibility of nodes selfishly optimising their positions by seeking connections in a network requiring fewer connections, without expanding network knowledge into second degree neighbourhood relationships.

The Lobby Index: In [7] a solution to the Diplomat’s Dilemma problem is presented by introducing a concept known as Lobby Index. In Lobby Index, to achieve a high index a node needs neighbours with at least the same number, or more, neighbours than the node itself in the current communication environment. Mathematically [7]:

$$l(x) = \max\{\, k : \deg(y_k) \geq k\} \quad (2.6)$$

Where, $l(x)$ = Lobby index of node x

k= Degree on node

y_k= Neighbors of node x; k=1, 2,...n

The concept of Lobby Index is depicted in Figure 2.6.

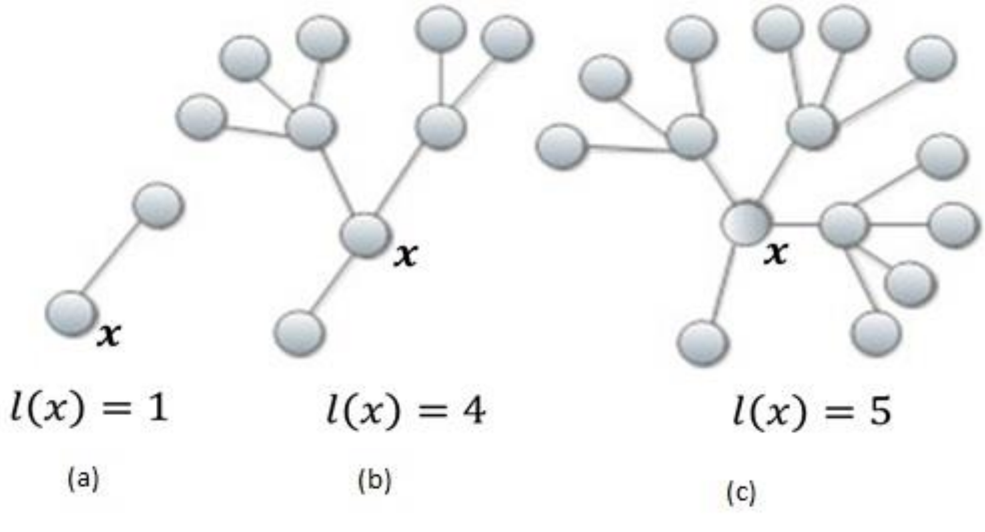


Figure 2.6 Lobby Index notion [89]

Fig. 2.6(a) shows that when only two nodes are communicating with each other, the lobby index of node ‘x’ is 1. In Fig. 2.6(b), one of the neighbours of node ‘x’ has 4 neighbours; therefore the lobby index of node ‘x’ is 4. Similarly, Fig. 2.6(c) shows that the lobby index of node ‘x’ is 5, because one of its neighbours has 5 neighbours. A node that has a high lobby index has neighbours with important connections in the society, giving it a high reach. Such a node, therefore, can use its neighbours effectively to forward messages for dissemination in the network, while keeping its own cost low.

Lobby Influence: In [3], I presented a social forwarding algorithm based on human social relationship patterns. This algorithm combines characteristics of both Bubble Rap [2] and Lobby Index [7], and is named Lobby Influence (LI). LI utilises both node popularity and the popularity of a node's neighbours. The concept observes that apparently unpopular nodes, deductively, could have a high number of popular neighbours, making them good candidates for information transmission. Either high access/reach or knowledge of other relevant nodes in the network can be achieved by targeting less popular nodes. Using such nodes to achieve message delivery to intended destinations could produce significant reductions in communication overhead.

For this algorithm, three assumptions are made:

- Each node must have a label to show its association with at least one community.
- Each node has one global rank and one local rank to define, respectively, global centrality (popularity) across the whole system, and local centrality within its local community. (A node may have multiple local ranks due to its association with many local communities, and thus may have multiple labels.)
- Each node has a lobby index indicating how well it is connected to its neighbours in the current network.

2.5 Chapter Summary

This chapter has provided a review of two interlinked but different communication networks: DTNs and opportunistic networks. The common factor between these two types of network is that both rely on store-and-forward messaging. The greatest difference between these networks is the method of determining routes between source and destination.

DTNs rely on the traditional topology of the internet, in which advance knowledge of routes is essential. Opportunistic networks, as their name suggests, do not require such prior knowledge. In DTNs, the links between gateways are permanent and transfer of data from mobile nodes occurs regularly to the same gateway. Opportunistic networks employ nodes as free agents, with each node able to store data and act as an independent gateway. The additional freedom that enables any node to act as a transport relay endorses the greater flexibility of opportunistic networks in comparison with DTNs.

This study shows clearly that the development of efficient routing/forwarding algorithms for opportunistic networks is determined by the function of these three main attributes: message delivery, time delay and communication cost.

The next chapter presents novel, socially-inspired opportunistic forwarding algorithms, which transfer messages to destinations using store-and-forward mechanisms.

Chapter 3

Enhanced Lobby Influence: criterion based information forwarding algorithm for opportunistic networks

This chapter presents a novel opportunistic forwarding technique known as Enhanced Lobby Influence (ELI) to improve the overall message delivery and reduce the communication cost. ELI forwarding not only exploit popularity of nodes but also popularity of node's neighbour. Furthermore, it retains the information of direct delivery destination nodes. The results obtained for new algorithm are not only verified against synthetic movement model but also in real mobility datasets.

3.1 Introduction

The aim of research work presented in this chapter is to develop an efficient routing/forwarding algorithm for opportunistic network, which is not only efficient in terms of message delivery but also cost effective. There are two major challenges in these networks 1) location of the recipient node 2) communication cost. Since nodes in the network do not have prior knowledge of recipients, therefore, the message forwarding is based on some criteria. When a node encounters with another opportunistic node, the forwarding criteria dictates to keep the message or forward it to the encountering node. This chapter presents an efficient opportunistic forwarding technique named as Enhanced Lobby Influence (ELI), to improve overall message delivery and cost effective communication, as compare to its predecessor Lobby Influence (LI).

Two major factors have influenced the design of LI algorithm presented in [3]. Firstly, if popularity of a node in a network based on the average of previous encounters is the criteria for node selection. This may be very cost extensive because every other node present in a network search for these popular nodes. Moreover, these popular nodes may have to keep messages for longer period of time until find the appropriate node for further transmission, as a result can be overburdened. Secondly, there is no assurance that the most popular nodes can always resolve a query and find the appropriate recipients. In fact, there are chances that buffer of these popular nodes may fill quickly as a result no room for new messages or TTL of message may expire before it actually reaches to the recipient. In order to address these issues, LI utilises the concept of community and centrality as presented in Bubble Rap (BR) [2] and also combines the Lobby Index as presented in [7], for details please see section 2.4.3. Lobby index shows the relation of a node with its neighbours, provided if its neighbours have at least equal or more neighbours (degree) than node itself. This idea makes sure that a node with high lobby index has set of well-connected neighbours and these well-connected neighbours have their own neighbours as a result a high degree of network knowledge can be achieved. LI algorithm increases the capabilities of BR, by not only targeting popular nodes but also uses the influence of neighbours of neighbours. No doubt not only information forwarding feature offered by LI has certainly upgraded total information delivery but also has shortened the delays in the environment of opportunistic communication networks. But yet, LI carries a downside with reference to upswing network communication cost in relation to current social forwarding algorithm like Bubble Rap.

The new technique presented by ELI demonstrates an optimised knowledge based information forwarding as compare to its predecessor LI. ELI efficiently progresses whole information delivery like its predecessor LI along with reduced communication cost. Basically ELI permits nodes to retain information of last recipients to which they have delivered information directly. ELI mainly gives intelligence to nodes to keep track of nodes they met as final recipient. If any midway node catches information to deliver for a recipient, which they recognize directly or has come across in any earlier information delivery as final recipient, should stop this information forwarding and retains it until they find final recipient themselves. As a result a notable volume of traffic is reduced by not forwarding to the irrelevant nodes in the network. The proposed algorithm is experimented on two types of movement models, synthetic movement model such as Working day movement (WDM) [8] and real mobility traces such as Cambridge [17], Reality [18] and Sassay [19] datasets. Results of the experiment revealed that ELI surpassed LI in both grounds such as with respect to efficient information delivery and dropping considerable amount of communication cost, respectively.

The rest of the chapter organized as follows: Section 3.2 gives the detail literature review on state of the art forwarding techniques in opportunistic networks. Section 3.3 presents Enhanced Lobby influence algorithm and forwarding mechanism in opportunistic environment. Section 3.4 presents network modelling that include detail discussion on simulator used, scenarios and simulation setup. Section 3.5 presents experimental results of synthetic and real mobility traces along with detail discussion. Finally, section 3.6 ends with chapter summary.

3.2 Research Challenges

The communication cost observed in simple flooding the opportunistic network is significantly reduced in Epidemic routing [1]. The Epidemic routing reduces the number of duplicate packets by not allowing packets tagged with same IDs twice to same node. Nevertheless, it does not stop sending irrelevant packets all over the network, and as a result the communication cost of this algorithm is still very high. To address this issue, a social based forwarding algorithm known as Bubble Rap (BR) [2] is proposed by Hui. BR is based on the concept of community and centrality, where nodes form communities to show their association with subset of nodes within the network. These nodes can be reached by exploiting betweenness centrality i.e. how many times a node come across as a message carrier during previous course of communication. The betweenness centrality in BR is taken from the analogy of person popularity in his social circle; the popular persons have more relations with other members of community, thus are ideal candidates to use as information forwarders. This message forwarding technique decreases the overall duplicate packets in the network and points the traffic to relevant destination nodes. However, drawback of this technique is an increase of load on popular nodes and buffer of these nodes can overflow very rapidly, as a result, packet loss can increase.

The BR highlighted the importance of social based algorithm, where content forwarding in opportunistic networks can improve by inferring analogies based on human relationships in a society. However, there are other algorithms that exploit human relationships analogies differently. For instance, a concept of exploiting individual with popular neighbours in a society is presented in the diplomat's dilemma [9], taken from the analogy that a diplomat has a high influence in a society, because his contacts are mainly with influential members of society. These individual can thus have more knowledge in the society, which give them more power with minimum effort of making personal relations. Based on diplomat's dilemma, Korn et al [7] presented a metric known as Lobby Index that defines "a node has high lobby index if its neighbours have at least equal or more neighbours than the node itself" [7].

Lobby Influence [3] is another social based algorithm that combines the characteristics of both the popularity of a node, as presented in [2], and the popularity of the node's neighbour, as presented in [7]. This algorithm is based on assumptions that apparently un-popular nodes might have popular neighbours and thus can be exploited for information transmission. By the help of these nodes, a high access or knowledge of other relevant nodes in the network can be gathered, which eventually help to deliver the messages to intended recipients. The LI has significantly improved the overall delivery ratios in opportunistic networks; however, it proved to be costly in terms of communication overhead.

In order to address the challenges such as delivery ratio and Cost observed in previous state of the art algorithms, next section presents novel opportunistic forwarding algorithm.

3.3 Enhanced Lobby Influence (ELI) Algorithm

This section gives detail discussion on mechanism of ELI message forwarding and the algorithm.

3.3.1 Knowledge Based Content Forwarding

ELI uses the same concept as described in LI, with the addition of keeping record of previous direct encounter with destination nodes. Keeping previous record of direct encounters have following objectives:

- ELI is based on assumption that when a node directly deliver content to final destination node, this means that node is member of same community as the destination node or in case of human relationship analogy that node can be a close relative, friend or colleague. The probability of meeting with the same destination node in future is very high. Keeping this information in node's database may help not to transmit unnecessary traffic to irrelevant nodes, thus can decrease overall network communication cost.
- Keep the size of node's database small, because in opportunistic networks there is no prior knowledge of route to the destination node. No way can a node store information of every forwarding node used for previous communication, only most relevant information is allowed to store in node's database such as IDs of destination nodes.

- When a forwarding node receives a packet for a destination node whose information is available in node's database, simply keeps the packet of that particular destination until meets personally to deliver the content.

In order to understand the knowledge based content forwarding concept, consider figure 3.1, where ELI illustrates observations based on which it reduces the communication cost but at the same time makes content delivery efficient for intended recipients. When two nodes encounter each other, the current node forward content to the encountered node based on three criteria:

1) More popular: high centrality i.e. how many times a node takes part as a forwarding/intermediate node, defines its popularity, as presented in [2].

2) Popular neighbours: high lobby index i.e. seemingly un-popular nodes could have a high degree of popular neighbours and are thus, good candidates for information transmission, as presented in [7].

3) Knowledge based nodes: previously directly delivered content to same destination node.

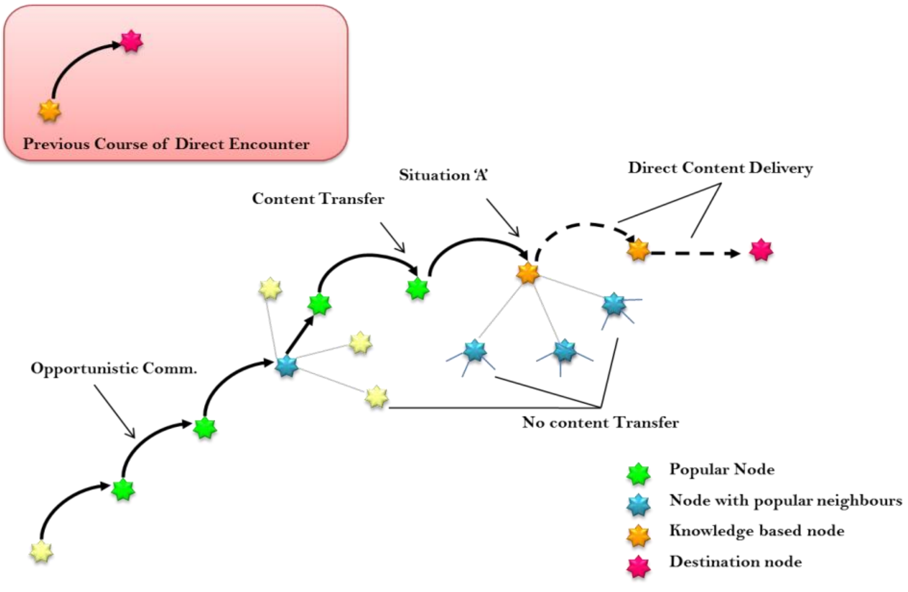


Figure 3.1 Enhanced Lobby Influence Concept

As depicted in figure 3.1, nodes only forward messages if the encountered node is either more popular or un-popular with high degree of popular neighbours, represented as green and blue nodes, respectively, this concept is inherited from Lobby Influence algorithm. Enhanced

Lobby influence comes into play when situation ‘A’ arises, as shown in figure 3.1. Node (represented in yellow) has popular neighbours, was previously engaged in delivering content to the intended destination node. This node does not transmit message any further to its neighbours, it keeps content until deliver it directly. Therefore, ELI restricts nodes not to send content further unnecessarily based on the previous knowledge of direct delivery to same destination node, as a result a significant amount of communication cost can be saved.

3.3.2 The Algorithm

The Enhanced Lobby Influence is the advance version of Lobby Influence algorithm. Therefore, all the concepts used in [3] are also considered in ELI algorithm. Label scheme [46] used in LI has been implemented, which assigns label to each node that describes its host community. For instance, in real world analogy a person’s office colleagues represent an office community; similarly a person’s home members represent home community; a person going for some evening event with friends represents friend community. Therefore, label defines node associativity with a particular community and a node may belong to different communities, thus have different labels. These small labels representing different communities, indeed simplify communication in opportunistic networks in terms of cost and locating destinations targets. Based on the label concept, the aim of ELI algorithm is to target destination nodes or nodes which are members of the same community as destination nodes. By targeting member nodes, ELI assumes that eventually the member nodes may take content to the member destination nodes.

For ELI algorithm, these rules are followed:

- Each node records the IDs of every destination node for which it acted as a direct communicator.
- Each node declares its community associations (labels).
- Each node calculates its popularity rank at local and global scale.
- Each node declares its neighbour’s highest degree with which it is directly connected i.e. high lobby index.

The algorithm is shown in figure 3.2 deals with a node at local and global scale. Local scale means that a node is present within its local community and global scale means a node is present among nodes associated with different communities. The algorithm takes following steps in order to forward content to encountered nodes:

Step 1: when a current node receives content for a particular destination, it first searches its database whether it had previously delivered to this particular destination directly. If yes, ELI keeps that content and wait for the direct encounter with that particular destination node. The current node keeps that content until meets with intended destination or discards it when time to live (TTL) expires. This process takes place every time a new node encounters irrespective of its local or global scale.

```
Begin
   Foreach (EncounteredNode_i) do
      If(previousDirectEncounterDestNodeDatabase(content) == true )
         {
                  If (EncounteredNode_i == Destination_Node)
                     {
                      EncounteredNode_i.addMessageToBuffer(content);
                     }
                  else
                     {
                      EncounteredNode_i.noContentTransfer();
                      }
          }
      else
          {
                if (getLabel(CurrentNode) == getLabel(Destination))
                   {
                  if (getLabel(EncounteredNode_i) == getLabel(Destination)) &&
                  getLabel(EncounteredNode_i) == getLabel(Destination)) &&
                  getLobbyInfluenceLocalStatus(EncounteredNode_i) == true)
                      {

                                EncounteredNode_i.addMessageToBuffer(content);
                   }
                    }
                else
                   {
                  if (getLabel(EncounterNode_i)==getLabel(destination)) ||
                  getLobbyInfluenceGlobalStatus(EncounteredNode_i)==true)
                        {


                                EncounteredNode_i.addMessageToBuffer(content);
                    }
                     }
           }
 End



getLobbyInfluenceLocalStatus(EncounteredNode_i)
      {
          if ((getPopularityLocal(EncounteredNode_i)==high) ||
           (getLobbyIndex(EncounteredNode_i)==high) ||
           (getLobbyIndex(EncounterNode_i)==Equal))
                 return true;
          else             return false;
       }

getLobbyInfluenceGlobalStatus(EncounteredNode_i)
       {
           if ((getPopularityLocal(EncounteredNode_i)==high) ||
            (getLobbyIndex(EncounteredNode_i)==high) ||
            (getLobbyIndex(EncounterNode_i)==Equal))
                  return true;
            else return false;
      }
```

Figure 3.2 Enhaced Lobby Influence Algorithm

Step 2: when a current node does not contain information about direct encounter for a particular destination node, in that case current node may come across two situations. a) Local Scale: at local community level, when a node encounters another node, this means that both nodes have same labels. The content forwarding decision made on local community popularity level and lobby index. If the encountered node has high lobby index irrespective of its popularity, the content transfer occurs. However, if both nodes have same lobby index in that case content transfer occurs based on high popularity. If none of these conditions met, the current node keeps the content and wait for suitable node or until TTL expires. b) Global scale: at this level, current node is forwarding contents at global scale. The current node keeps on forwarding contents until it finds destination node or the member of destination node's community. The forwarding decision at global level is based on the global popularity or high lobby index of the encountered node. Once a suitable forwarding node is found at global scale the current node removes the original message from its database to reduce the resource utilisation. If none of these conditions met, the current node keeps the content and wait for suitable node or until TTL expires.

3.4 Network Modelling

This section gives an overview of the simulator used for the purpose of this piece of research. Furthermore, this section also discusses various scenarios with simulation parameter used in these experiments including overview of simulator used.

3.4.1 Simulator

To evaluate ELI algorithm, opportunistic networking environment (ONE) simulator [47] is used. This simulator is specifically designed to test the opportunistic concepts in different built-in synthetic movement models as well as existing mobility traces. Node movements are implemented through these movement models. In ONE simulation world, nodes make connection based on communication range, bit rate and location. ONE is an agent-based discrete event simulation engine. The engine is divided into many sub-modules that implements main simulation functions. The engine updates each of these modules at every simulation step. These modules are used to perform different task for simulation engine, mainly: modelling of node movement, inter-node contacts, routing and message handling.

Also, results for analysis purposes are collected through modules such as visualization, report and post processing tools. Figure 3.3 shows the block diagram of ONE simulator sub-modules and their interactions.

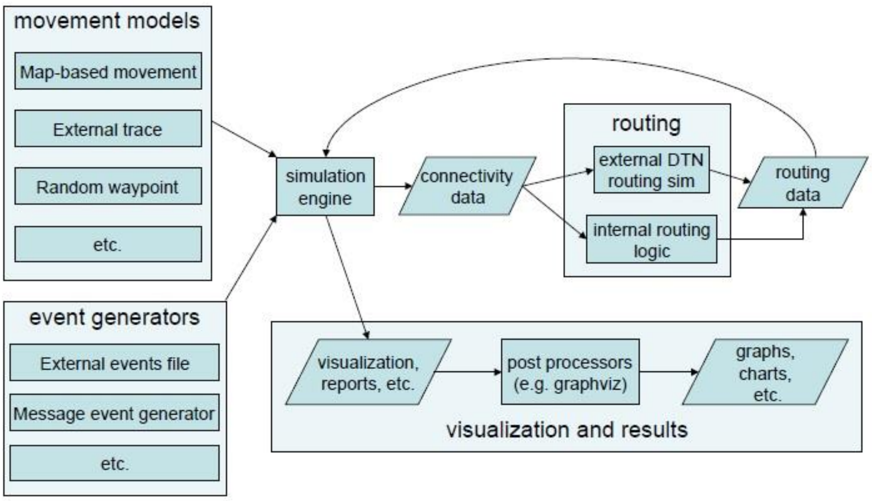


Figure 3.3 Sub-modules in ONE Simulator [47]

3.4.2 Integration of ELI in ONE simulator

ONE simulator is modular in nature as shown in figure 3.3. It is designed in such a way that each module work independently yet perform services for other modules. To perform experimentation for ELI algorithm, mainly five modules are used such as Map-based movement, external traces, message event generator, routing and reports. In Map-based movement module, working day movement model is used for synthetic experimentations. In External traces module, three real mobility traces datasets are used i.e. Cambridge, Reality and Sassy. Message event generator module is used to generate messages during the simulation. In routing module, ELI algorithm is implemented according to the pseudo code shown in figure 3.2. Once the simulation is performed the results are then stored in files under report module for post processing.

3.4.3 Scenario Environments

ELI algorithm is tested against two type of simulation environment: 1) Synthetic 2) Real mobility traces. Synthetic environment gives the flexibility to change simulation parameters as per requirement of the scenario to check robustness of the algorithm. In synthetic experiments, ELI is tested in working day movement model (WDM) [8]. In WDM, nodes mimicking the behaviour of humans in daily life, i.e. a node start day from home, use transport (walk, cars and buses) to reach destinations (office, market and home) and finally nodes end day by reaching back to home. Real mobility traces are the datasets that contains data gathered from experiments conducted by different researchers/organisations and made it public for educational purposes. ELI algorithm is tested against three real mobility traces: Cambridge, Reality mining and Sassy.

3.4.3.1 Synthetic Scenario

Average humans tend to live in society where they adopt specific living patterns based on their daily life. Human have daily routines where they go to office in the morning, go for the shopping and go back to the home in the evening, this represents reality of the life. The algorithms which are being experimented in this research based on the analogy of human behaviours; therefore it is very important that performances of these algorithms should be tested against the model that represents real life patterns. To approach realistic model, working day movement (WDM) [8] is adopted in this simulation. WDM model is based on the map of Helsinki city which is divided into different districts. These districts represent markets, restaurants, shopping malls, housing colonies and offices. In simulation, nodes start its day from their homes, early in the morning they will start off by leaving their houses to go different districts either for shopping or work. Nodes are moved based on the Helsinki map in such a way that when there is a highway, nodes will move with the speed of car or bus and where there is pedestrian paths, nodes will move with human speed. Since nodes are moved in predefined paths based on Helsinki map, therefore generate a pattern same as a real life person who start his day from home leave for office or shopping. Therefore, WDM model is ideal synthetic model for simulation purposes where human daily life patterns are required to study.

In WDM model, the central areas of this model are divided into 4 artificial districts A, B, C and D, please see [8] for more details. For this simulation, this thesis considers districts A, B and C. District A is the busiest district, as considered by [3], which is connected with districts B and C through overlay districts E and F respectively. Different offices, shopping areas and meeting spot are present in those districts. Nodes go to these meetings point through their own car or by taking buses. Thus represents a real world scenario where different nodes have chance to meet with each other and the nodes which are far apart from each other may be connected through intermediate nodes. Table 3.1 shows the assignment of nodes, offices and meeting spots to the respective districts.

Table 3.1 District settings [3]

District	Nodes	Offices	Meeting Spots
A	30	30	4
B	30	10	1
C	30	20	2
E(A & B)	30	20	2
F(A & C)	30	30	4

3.4.3.2 Real Mobility Traces

In real mobility traces, three datasets are used. Explanation of each dataset is discussed here and there characteristics are shown in Table 3.2.

Cambridge Dataset [17]: In this dataset, mainly there were two types of student groups: undergraduate (year1/year2) and graduate students (Masters/PhD) from University of Cambridge Computer Laboratory. Several iMotes were distributed among the students and study conducted cover up to 11 days

Reality Dataset [18]: In this dataset, MIT conducted experiments that cover the overall period of nine months. 100 Bluetooth enabled smart phones were distributed among students and staff. The software in these phones recorded contacts with other devices of same breed. In order to save battery life, each device was allowed to scan then area in every 5 minutes.

Sassy Dataset [19]: In this dataset, total of 27 T-mote invent devices were distributed among students and staff members in University of St Andrews. The experiments were conducted up to 79 days. The devices were programmed to generate beacons in every 6.67 seconds to detect other invent devices or base stations in 10m range. These devices recorded timestamps of contact duration and device IDs.

Table 3.2 Characteristics of data sets

Experimental data set	Cambridge	Reality	Sassy
Device	IMote	Phone	T-mote
Network type	Bluetooth	Bluetooth	IEEE 802.15.4 Sensors
Duration (days)	11	246	79
Scanning interval (seconds)	600	300	6.67
Number of Devices	54	97	27

3.4.4 Simulation Setup

This section gives the detail discussion on simulation setup and parameters used in synthetic and real mobility experiments.

3.4.4.1 Simulation Setup for Synthetic Experiment

Working day movement model is used for synthetic experiments. The beauty of WDM model is that nodes activities are very close to the human daily life activities. In this movement model, nodes start off day from home, spend time in office, go for evening activities and finally come back home by the end of the day. During these movements, nodes have chance to meet with other nodes and nodes far apart from each other can be reached through intermediate nodes. For the best efficiency of the ELI algorithm, setting used as shown in table 3.3 are exactly the same as described in [3].

Table 3.3 Algorithm settings for LI & ELI

Parameters	**Value**
Community detection algorithm	K Clique
K	3
Familiar threshold	700
Centrality algorithm	C window
Centrality time window	3600 (s)
Computation interval waiting time	300 (s)
Number of time intervals to average	3

Devices considered in this experiment are equipped with Bluetooth capabilities. Each device is capable of transmitting packets at speed of 2Mbits/s up to 10m range. This simulation considers activities of nodes for one day. The length of the day is approximately 16 hours because after that a node assumes to be at home. Table 3.4 summarize the parameters used in this experiment.

Table 3.4 Parameters used in WDM scenario

Parameters	Value
World's size for Movement Model	10000 X 8000m
Total simulation time	57000s
No. of Hosts [pedestrians, buses]	[150, 10]=160
Message TTL (time to live)	960 mins
Time to move nodes in the world before real simulation commence	7200s
Nodes speed [pedestrians, buses]	[0.5-1.5, 7-10]m/s
Nodes pause time [pedestrians, cars, trams]	[0-0, 10-30]s
Message sizes	500KB-1MB
Message creation interval	15-25s
Air data transmit speed	250kbps
Transmit range	10m
Working day length	28800s
Probability to go shopping after work	0.5
Own car probability	0.5
Range of message source/destination addresses	0-159 nodes
Queue sizes	0,20,40,60,80,100,120,140,160,180 in MB
No. of each experiment runs	10

3.4.4.1 Simulation Setup for Real Mobility traces Experiment

In order to test LOC algorithm in real mobility traces, we again used java based Opportunistic Networking Environment (ONE) simulator [47]. ONE simulator provides two types of classes to link external (real) mobility traces 1) ExternalMovementReader and 2) ExternalEventsQueue. The ExternalMovementReader class reads time stamped node locations from external mobility dataset and moves the node in the simulation accordingly. The two nodes in simulation environment exactly connect or disconnect as per recorded in real mobility dataset. The ExternalEventsQueue class can read events from the file and create number of messages and its size as per define in external message event file. ONE also provides another built-in message generation class known as MessageEventGenerator. This is a simple message generator class that creates uniformly distributed message creation patterns with configurable message creation interval, message size and source/destination host ranges. In these experiments, we used ExternalMovementReader class to read node movements from real mobility traces and MessageEventGenerator to create messages from ONE's built-in message generation functionality.

Total simulation time is equal to the final timestamp in respective datasets. Number of hosts present in simulation world is as per original number of participants. Varied length of message TTL used between 2 minutes to 3 weeks. In these experiments nodes speed is considered as per average speed of human. Transmission range of each node is 10 meters. The message queue size of each node is 12MB throughout the course of simulation. All nodes are participating as message sender/receiver. Table 3.5 summarises the parameters used in simulation.

Table 3.5 Parameters used in Real mobility scenarios

Parameters	**Value**
Total simulation time	As per dataset
No. of Hosts [pedestrians, buses]	As per dataset
Message TTL (time to live)	Varied [2mins – 3 weeks]
Nodes speed [pedestrians]	[0.5-1.5]m/s
Message sizes	500KB-1MB
Message creation interval	15-25s
Air data transmit speed	250kbps
Transmit range	10m
Movement Model	Map based
Range of message source/destination addresses	all nodes
Queue sizes	12MB
No. of each experiment runs	10

3.5 Results

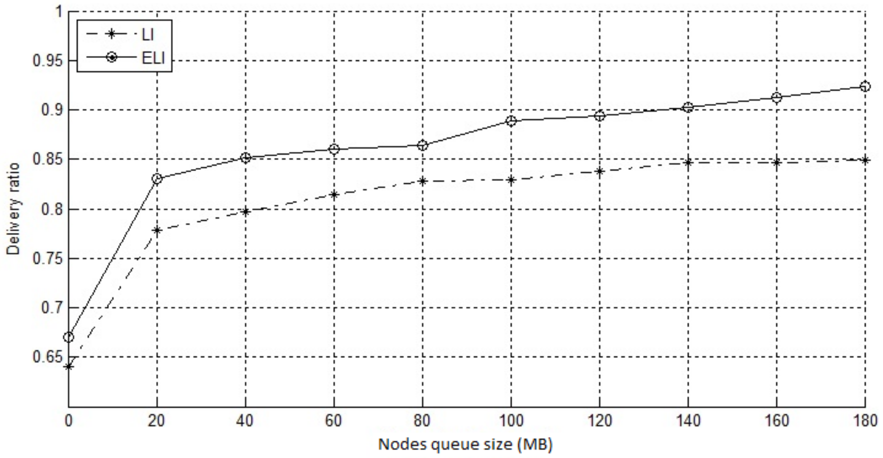
This section gives the detail discussion on results obtain from the experiments performed in both synthetic and real mobility traces.

3.5.1 Results of Synthetic Experiments

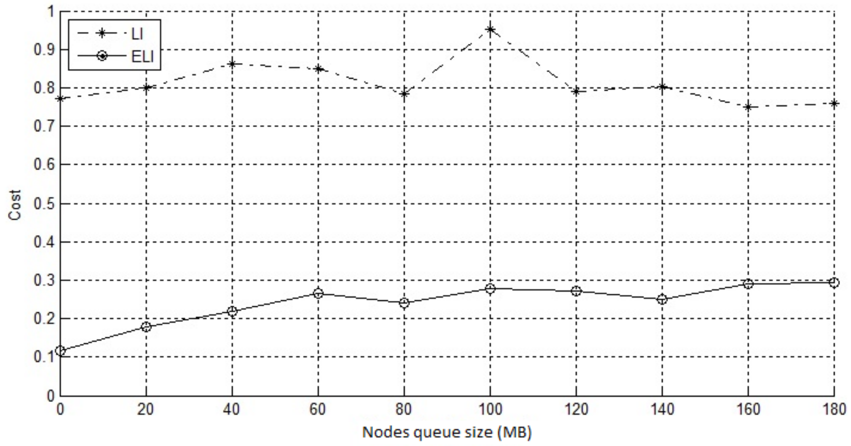
Sections 3.4.2.1 and 3.4.3.1 give the detail overview of scenario and simulation setup used for these experiments, respectively. Two algorithms LI and ELI are evaluated by changing the queue size of the nodes and their results are compared. Overall performance of the network can greatly improve by increasing the size of queue. With large queue size a node can store more messages and chances of dropping packets due to queue over-flow lessen. Ten experiments are performed for each queue size using different seeds. Due to high computation requirement for ONE simulator, multiple high performance computers are used. Two metrics are compared to evaluate the performance of each algorithm: 1) Message delivery: numbers of packets reach at the intended destinations s) Cost or Forwarded messages: total number of messages exchanged (including duplicates) among nodes, defines the cost of the network, which ultimately effects the utilisation of system resources (bandwidth and energy). Each graph shown in this section contains two curves representing behaviour of LI and ELI algorithms, respectively. X-axis represents varying queue sizes against which each graph is plotted.

Figure 3.4 (a) shows the number of messages received at destination nodes in working day model scenario. The graph shows that ELI outperforms LI in terms of message delivery. LI exploits both popular nodes and un-popular with popular neighbours (high influential nodes). ELI is inherited from LI, so naturally it possesses all the characteristics of LI. In addition to these characteristics, ELI makes a node to keep the record of those destinations for which it acted as a final relay node. The graphs show that, this observation we made for ELI proves to be true; in WDM model same nodes have chances to meet each other in office, home or evening meeting points. Therefore, by allowing these nodes to keep the message until deliver directly to destination nodes, indeed improves the overall delivery rates.

Figure 3.4 (b) shows the cost or overhead of the network communication for delivering message from source to destination during the experiments and plotted its normalised value between 0 and 1 for graphical purposes. The cost is calculated as by subtracting number of message delivered at destinations from the total number of messages relayed or forwarded in the network. LI proves to be more costly because selection of forwarding node is not only based on popularity but also on influential nodes; this naturally increases the communication cost. ELI outperforms its predecessor LI, because ELI stop forwarding the messages, if it finds the message is intended for that destination for which it delivered before. This observation has significantly reduced the overall network communication cost.



(a)

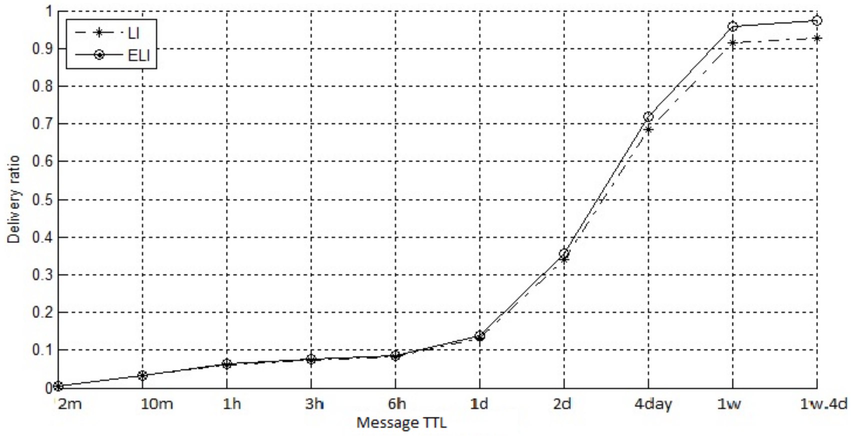


(b)

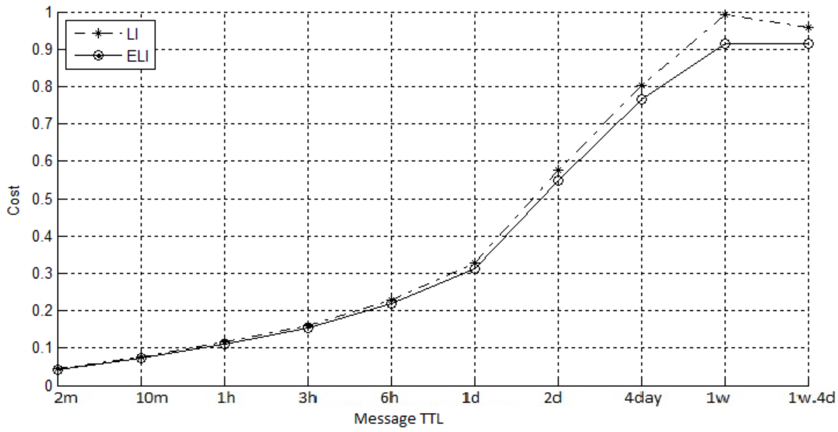
Figure 3.4 Performance of ELI in WDM (a) Average delivery ratio (b) Delivery cost (normalised)

3.5.2 Results of Real Mobility traces Experiments

Sections 3.4.2.2 and 3.4.3.2 give the detail overview of scenario and simulation setup used for these experiments, respectively. The graphs discussed in this section represents the performace of two algrithms LI and ELI. These algorithms are evaluated against varying duration of message TTL (time to live) in three datasets Cambridge, Reality and Sassy, respectively. The variation in message TTL help our study to assess algirthms on real datasets, which may comprise of days, weeks or even months. In these graphs, two metrics delivery ratio and cost or number of forwarded messages are plotted against message TTL, respectively. Each graph contains two curves LI and ELI, respectively.



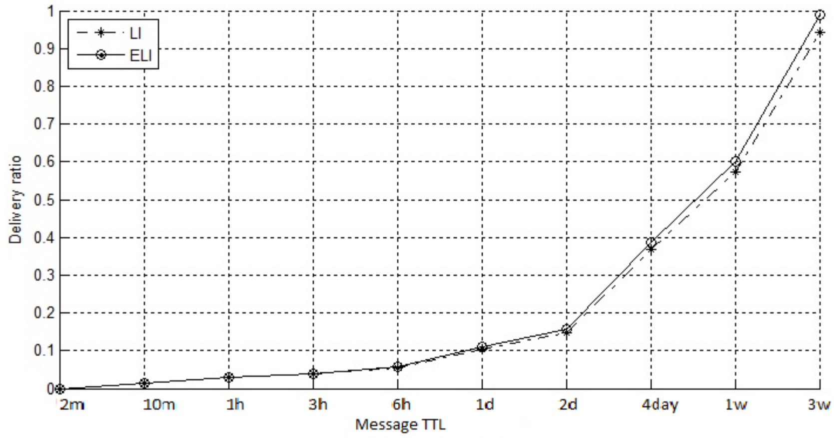
(a)



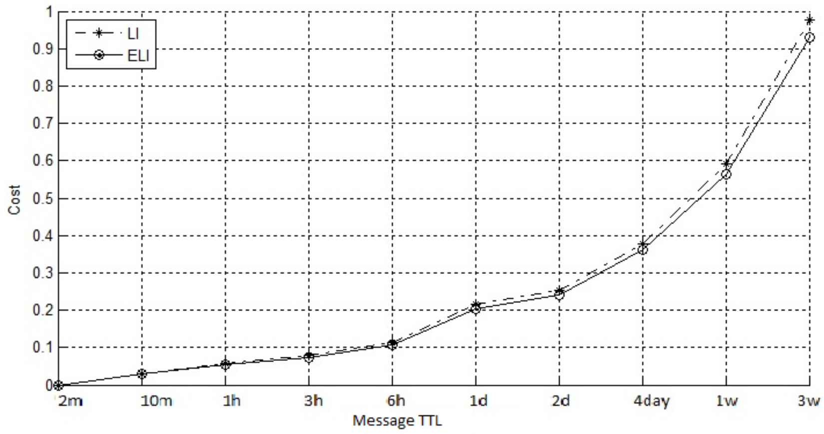
(b)

Figure 3.5 Performance of ELI in Cambridge dataset. (a) Average delivery ratio (b) Delivery cost (normalised)

Figure 3.5 shows the average delivery ratio and delivery cost at destinations in Cambridge dataset. In Cambridge dataset, total simulation duration of simulation is equivalent to almost 11 days. Figure 3.5 (a, b) shows that ELI performance is better than LI performance in terms of message delivery and cost. LI may use one or both message forwarding criteria among the following two 1) popular nodes 2) un-popular nodes with popular neighbours. Although the criteria used by LI has improved the overall delivery ratio in network, but still it potentially leads the message forwarding to the dead end, where message eventually discards after TTL expires. ELI addresses the issue faced during the LI performance. ELI has the all properties of LI, as it is inherited from LI. In addition to that, ELI also allows final forwarding node to keep records of all the recipients it acted as last forwarding node in the chain of previous course of communication. If the same final forwarding node recieves the message for the recipient it delivered previously, it will keep that message until directly encounters with final recipient. In this way, a great deal of unnecessary message forwarding can be stopped as a result overall communication cost improves. The observation based on which ELI works show better results, as shown in figure 3.5 (a) and 3.5 (b).



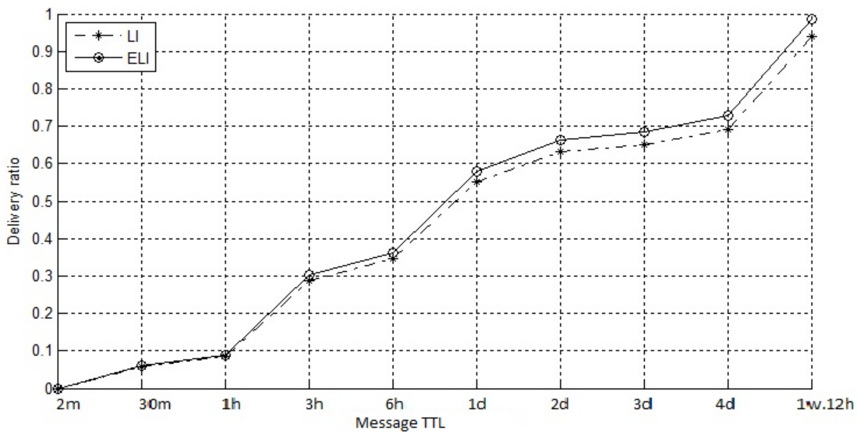
(a)



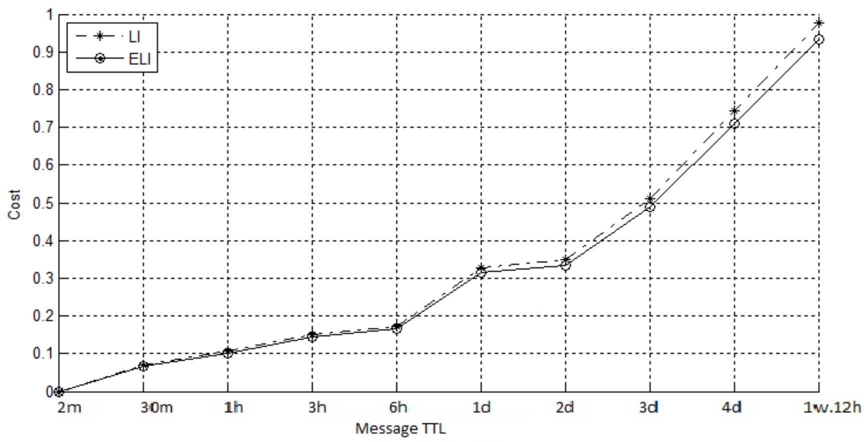
(b)

Figure 3.6 Performance of ELI in Reality dataset (a) Average delivery ratio (b) Delivery cost (normalised)

Figure 3.6 shows the average delivery ratio and delivery cost at destinations in Reality dataset. Although, Reality dataset comprises of 9 months of information, but in this simulation we consider 3 weeks of information where the contact between nodes is highest. Fig 3.6 (a) and (b) shows that ELI again proves to be the better algorithm than LI in terms of delivery ratio and communication cost. This proves our assumption that if the final forwarding node keeps the history of its previous direct delivery to the recipients; not only improves the overall delivery ratio but greatly improves overall communication cost in the network. In reality data set we have limited numbers of nodes to experiment with, if there are significant number of nodes present, we can see clear difference in cost reduction as in case of WDM scenario.



(a)



(b)

Figure 3.7 Performance of ELI in Sassy dataset (a) Average delivery ratio (b) Delivery cost (normalised)

Figure 3.7 shows average delivery ratio and delivery cost in Sassy dataset. Sassy dataset contains 79 days of contact information. Again ELI message forwarding criteria makes it better algorithm than LI in terms of message delivery and cost. As we can see from figure 6 that the difference between curves becomes more evident when number of nodes in the data set starts to increase. This clear the fact that graph curves of ELI in WDM model seems better than reality mobility dataset because in WDM more nodes are present to play with.

3.6 Chapter Summary

In this chapter, a novel opportunistic forwarding technique ELI is proposed. ELI addresses short comings observed in its predecessor Lobby Influence (LI) in terms of delivery ratio and communication cost. Simulation results have confirmed that the observation based on which Enhanced Lobby Influence is designed turns out to be accurate. Enhance Lobby Influence not only selects forwarding nodes as does by its predecessor Lobby Influence but also keeps the knowledge of previous direct encounters with intended recipients. This makes un-popular nodes with popular neighbours to share the burden of popular nodes but also stop forwarding the content unnecessarily to other nodes, if destination is known during the previous course of direct communications.

Finally, results confirmed that this algorithm is superior to LI in relations with information delivery and communication cost and is an alternative for delay tolerant opportunistic networks. It is also observed that, experimental results show very minor difference between ELI and LI curves in real mobility datasets. This is due to the fact that, in real mobility datasets the information gathered in specific scenarios with limited number of nodes present in these experiments. Whereas, in synthetic movement model such as WDM, the difference between curves become more evident as more nodes are present to play with.

Next chapter will discuss another opportunistic forwarding technique, which is based on location proximity of the node in the network.

Chapter 4

LOC algorithm: Location-aware opportunistic forwarding by using node's approximate location

In previous chapter, a socially inspired opportunistic forwarding technique is discussed. This chapter presents another opportunistic forwarding technique based on exploiting location proximity of nodes in the network. The aim of this technique is to direct messages to the intended destinations in order to achieve increase in overall message delivery and keep the communication cost of the network to minimum. New algorithm is tested in synthetic movement model as well as in real mobility datasets.

4.1 Introduction

Unlike traditional networks such as wired networks, opportunistic networks nodes don't have prior knowledge of routes to the destination. In such networks, the challenge is to effectively deliver messages to the destinations while maintaining minimum communication costs. In opportunistic network any node can be utilised to forward information to intended destinations, provided that node can indeed forward information in the direction of destination node. Nodes have to forward messages to the intermediate nodes depending upon the probability of delivering message to its destination; the message may or may not deliver to the destination nodes. The easiest way to solve this issue is to flood messages throughout the network, but this kind of communication is not acceptable since it has degrading effects on network resources. Epidemic algorithm [1] has addressed this issue and reduced the communication cost significantly by not delivering the same packet to the same node twice. Though Epidemic algorithm has managed to reduce the cost, but it still floods the network in controlled manner.

To reduce the communication cost in the opportunistic networks, many social algorithms [2, 3] have been proposed. These social algorithms are fundamentally based on three centrality measures betweenness [4], degree [5] and closeness [6]. The main concept behind these algorithms is to exploit those nodes which have important significance in the network. The targeting of significant nodes improves the chances of delivering the messages to intended destinations. These important nodes may have the direct knowledge or they may know the other nodes that have knowledge of intended destinations. Based on similar concept, Bubble Rap [2] proposed the idea of exploiting popular nodes in the network. These popular nodes can act as efficient message forwarders as they have knowledge of many other nodes in the network. Bubble Rap has significantly reduced the communication cost as compare to Epidemic. However, popular nodes have to pay price in the form of quick resource exhaustion. Another socially inspired algorithm is Lobby Influence (LI) [3], which exploits important nodes on the basis of popularity [2] and popularity of node's neighbour [7]. According to LI algorithm, not only popular nodes have significance in the network but also those un-popular nodes are significant which have popular neighbours. LI has not only improved the overall message delivery ratio but also reduced the delays; however, its communication cost is still higher than Bubble Rap algorithm.

This chapter presents a location aware content forwarding algorithm using direction vectors, in short "LOC" algorithm. In LOC algorithm, source node is aware of its approximate destination position and its intended destination in the network by the help of Global Position System (GPS). The approximate position of source and intended destination node is used as reference values for intermediate nodes to direct messages towards intended destinations. The reference distance and direction values can be calculated from source to intended destinations by using direction vectors. The process of forwarding messages to intermediate nodes is very simple, forward messages to those nodes present closest to the reference values. By doing this, a great deal of message directivity is achieved. The new algorithm is tested against Lobby influence and Epidemic algorithms in synthetic model such as working day movement model (WDM) [8] and real mobility traces such as Cambridge [17], Reality [18] and Sassay [19] datasets. Simulation results have shown that LOC has outperformed LI and Epidemic significantly in all grounds. LOC not only improves the overall delivery ratio but at the same time it reduces the delay and also a significant reduction in communication cost.

The rest of the chapter is organized as follows: Section 4.2 gives the detail literature review on state of the art forwarding techniques in opportunistic networks. Section 4.3 presents Enhanced Lobby influence algorithm and forwarding mechanism in opportunistic environment. Section 4.4 presents network modelling that include detail discussion on simulator used, scenarios and simulation setup. Section 4.5 presents experimental results of synthetic and real mobility traces along with detail discussion. Finally, section 4.6 ends with chapter summary.

4.2 Research Challenges

The Epidemic algorithm [1] has successfully reduced the communication cost as observed in simple flooding of network. Epidemic algorithm has addressed this issue by stopping transfer of duplicate packets to the same nodes. However, the issue of communication cost still remains in this algorithm as it still floods the network by transmitting irrelevant packets in the network, though not duplicate ones. Bubble Rap (BR) [2] presented by Hui is a social based forwarding algorithm which addresses the issue of communication cost by employing the concept of community and centrality. Nodes in social context can form communities and relationship of these nodes to its respective communities can be exploited for the purpose of information dissemination. In order to reach these nodes, the BR proposed that betweenness centrality can be used to calculate the popularity of nodes in the network. Popular nodes have more knowledge of the network as they have been used many times as message carriers in the network, thus exploiting such nodes can improve the chances of message delivery. The BR has managed to reduce communication cost significantly as compare to Epidemic routing by directing messages only to those nodes which are popular ones. However, drawback of this algorithm is in the form of load on popular nodes as these nodes serve as forwarders for many less-popular nodes, thus can deplete resources very quickly. Besides, buffer of these popular nodes can overflow very quickly and this can cause increase in packet loss.

The BR is the first opportunistic forwarding algorithm that brings the use of social based forwarding techniques in limelight. The idea is simple that content forwarding in opportunistic networks can be incorporated with human social analogies. Based on similar concept, another technique known as diplomat's dilemma [9] is inferred from the analogy of diplomat. A diplomat has ties with influential people in the society, thus targeting these individual gives the more knowledge of the society. Based on the concept of diplomat's dilemma, another algorithm known as Lobby Index [7] presented by Korn et al. The Lobby Index introduces a Lobby Index metric that defines "a node has high lobby index if its neighbours have at least equal or more neighbours than the node itself" [7].

Lobby Influence [3] is another social forwarding technique that combines the properties of both Bubble Rap [2] and Lobby Index [7]. LI is based on the concept that not only popular nodes but also unpopular nodes with popular neighbours can be exploited for the purpose of message forwarding. By targeting these nodes, knowledge about the network can be gathered as a result high reach can be achieved, which ultimately help to locate intended destinations for message delivery. The LI proved to be better algorithm in terms of overall message delivery and speed; however, it has more overhead than BR algorithm.

In order to address the challenges such as delivery ratio and Cost observed in previous state of the art algorithms, next section presents novel opportunistic forwarding algorithm.

4.3 Location-Aware Opportunistic Content Forwarding (LOC) algorithm

This section provides the detail discussion on LOC algorithm that includes the concept of magnitude and direction vectors, LOC message forwarding process and the algorithm.

4.3.1 Magnitude and Direction Vectors

If the co-ordinates of destination node are known then distance and direction between source and destination nodes can be calculated using vector formulas. The magnitude of vector is the distance between two points, initial point ‘A’ and final point ‘B’, as shown in figure 4.1.

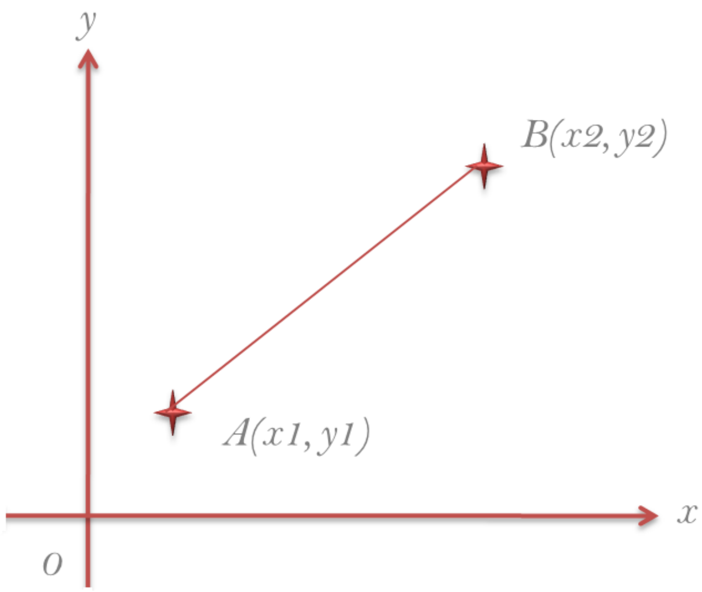


Figure 4.1Graphical representation of vector $\overline{AB}$

Mathematically the formula can be written as:

$$\overline{|AB|} = \sqrt{(x2 - x1)^2 + (y2 - y1)^2} \tag{4.1}$$

Where, (x1, y1) and (x2, y2) represent initial and final co-ordinates of nodes, respectively.

The direction of vector $\overline{AB}$ is the formation of horizontal angle between initial point ‘A’ to the final point ‘B’. Mathematically the formula can be represented as:

$$\theta = \tan^{-1}(y2 - y1)/(x2 - x1) \tag{4.2}$$

Where, (x1, y1) and (x2, y2) represent initial and final co-ordinates of nodes, respectively.

4.3.2 LOC Forwarding Technique

To better understand the content forwarding process of LOC algorithm in opportunistic network, consider figure 4.2. Source node ‘S’ wants to transfer messages to the destination node ‘D’. It is assumed that initially source node ‘S’ knows the location (X-Y coordinates) of destination node ‘D’ in the network. The source node ‘S’ calculates the direction (angle) and distance from its position to the destination node ‘D’ using direction vectors formulas, as given in “(4.1)” and “(4.2)”, and store these initial calculations as reference values. In figure 4.7, experiments have shown that rather than restricting nodes to select exact inline reference direction, nodes are allowed to select those nodes as well which lies within range of $\pm 5^0$. Figure 4.7 shows that by allowing $\pm 5^0$ range selection criteria, nodes have achieved high message delivery ratio at destinations compare to inline selection criteria, therefore $\pm 5^0$ is recommend for efficient content forwarding. When source node ‘S’ encounters with any intermediate node (in this case ‘a’ or ‘b’), it first estimates direction (angle) that must be in the range of $\pm 5^0$ compared to the reference values. If multiple intermediate nodes are present within $\pm 5^0$ range of the reference destination angle the source node calculates the distance of intermediate nodes with reference destination distance and selects node closer to the destination node. Once the intermediate node is selected, source node forwards message and destination approximate location to the intermediate node. Now intermediate node becomes the source and follows the same process until meets destination or time to live (TTL) of the message expires. Consider the situation ‘A’ in figure 4.2, where node ‘S’ selects node ‘b’ as a forwarding node because the reference angle of node ‘b’ is closer to the destination node ‘D’, although both nodes ‘a’ and ‘b’ are approximately at similar distances. In situation ‘B’, although angles of node ‘a’ and node ‘b’ seem equal from reference angle, however source node ‘S’ chooses node ‘a’ because its distance is closer to destination node ‘D’ as compared to node ‘b’.

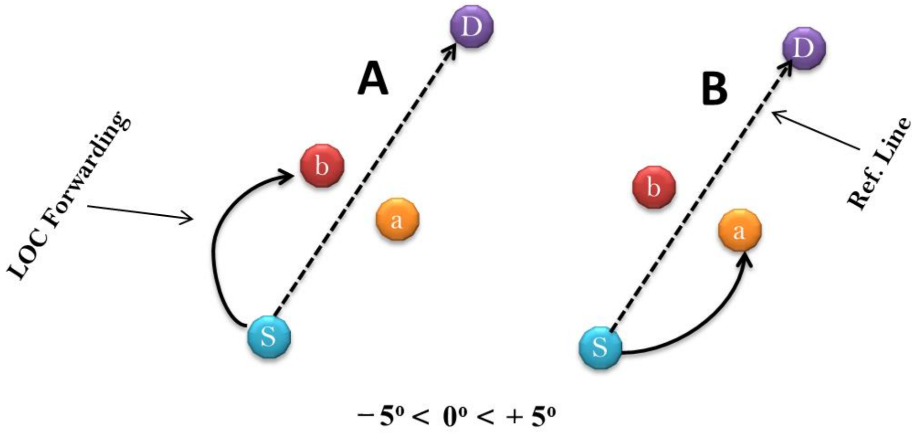


Figure 4.2 Location-aware Content Forwarding

4.3.3 The Algorithm

To materialize the LOC forwarding, it is assumed that the source nodes have the knowledge of approximate location of its recipients in the network with the help of Global positioning system (GPS). The forwarding decision of LOC algorithm is based on the direction and distance of the current node to the approximate location of destination node. In order to forward information using this algorithm, each node must have following properties and processes:

1. Each node has the approximate knowledge of its ‘X’ and ‘Y’ co-ordinates.

2. Initially, source node computes its direction (angle) and distance towards the destination node with the help of formulas “(4.1)” and “(4.2)”in section 4.3.1 to get the reference values.

3. When a source node encounters the intermediate node, it asks co-ordinate information from encountering node. The source node computes the direction and distance of encountering node towards the destination node with the help of reference values.

4. If the angle (direction) of encountering node is larger than reference angle $\pm 5^0$, source node keeps the message until finds the more suitable node. If multiple encountering nodes are present within $\pm 5^0$ of reference angle then source node selects encountering node

having closer distance to the destination reference value. Results in section 4.5.1 shows that allowing $\pm 5^0$ difference indeed increases overall content delivery efficiency in opportunistic network.

5. If the criteria in step 4 is met, then source node performs two tasks:

- Forward the message.
- Forward the approximate co-ordinates of destination node.
- The encountering node now acts as source node and performs the same process from step 2, until find the destination.

LOC Algorithm: For this algorithm, following assumptions are considered.

- Each node updates its coordinates in specific interval of time i.e. after 5 minutes.
- The approximate coordinates of destination node are known to the original source nodes. Intermediate (forwarding) nodes get approximate recipient location from source node during the exchange of information.
- The nodes with $\pm 5^0$ difference from reference angle consider as potential forwarding nodes.

Figure 4.3 shows the pseudo code for the Location-aware Opportunistic content forwarding algorithm.

```
Begin
Calculate reference distance and angle from the current node to the destination node
  For each encountered node, perform
      If encountered node's angle is between ±5 0 than reference angle, perform
          If encountered node's distance is less than reference distance, perform
             Forward message and approximate destination co-ordinates to the encountered node
 Keep on the same process, until meet the destination node
End
```

Figure 4.3 Pseudo code for LOC algorithm

4.4 Network Modelling

This section gives an overview of the simulator used for the purpose of this piece of research. Furthermore, this section also discusses various scenarios with simulation parameter used in these experiments.

4.4.1 Scenario Environments

LOC algorithm is tested against two types of simulation environment: 1) Synthetic 2) Real mobility traces. Synthetic environment gives the flexibility to change simulation parameters as per requirement of the scenario to check robustness of the algorithm. In synthetic experiments, LOC is tested in working day movement model (WDM) [8]. In WDM, nodes mimicking the behaviour of humans in daily life, i.e. a node start day from home, use transport (walk, cars and buses) to reach destinations (office, market and home) and finally nodes end day by reaching back to home. Real mobility traces are the datasets that contains data gathered from experiments conducted by different researchers/organisations and made it public for educational purposes. LOC algorithm is tested against three real mobility traces: Cambridge, Reality mining and Sassy.

4.4.1.1 Synthetic Scenario

Working day movement model (WDM) is used for synthetic scenario experiments. Average humans tend to live in society they adopt specific living patterns based on their daily life. Human have daily routines where they go to office in the morning, go for the shopping and go back to the home in the evening, this represents reality of the life. The algorithms which are being experimented in this research based on the analogy of human behaviours; therefore it is very important that performances of these algorithms should be tested against the model that represents real life patterns. To approach realistic model, working day movement [8] is adopted in this simulation. In this model a map of Helsinki city is presented where its central areas are divided into 4 artificial districts A,B,C and D, please see [8] for more details. For this simulation, this thesis considers districts A, B and C. District A is the busiest district, as considered by [3], which is connected with districts B and C through overlay districts E and F respectively. Different offices, shopping areas and meeting spot are present in those districts. Nodes go to these meetings point through their own car or by taking buses. Thus represents a real world scenario where different nodes have chance to meet with each other and the nodes which are far apart from each other may be connected through intermediate nodes. Table 4.1 shows the assignment of nodes, offices and meeting spots to the respective districts.

Table 4.1 District settings [3]

District	Nodes	Offices	Meeting Spots
A	30	30	4
B	30	10	1
C	30	20	2
E(A & B)	30	20	2
F(A & C)	30	30	4

4.4.1.2 Real Mobility Traces

In real mobility traces, three datasets are used. Explanation of each dataset is discussed here and there characteristics are shown in Table 4.2.

Cambridge Dataset [17]: In this dataset, mainly there were two types of student groups: undergraduate (year1/year2) and graduate students (Masters/PhD) from University of Cambridge Computer Laboratory. Several iMotes were distributed among the students and study conducted cover up to 11 days

Reality Dataset [18]: In this dataset, MIT conducted experiments that cover the overall period of nine months. 100 Bluetooth enabled smart phones were distributed among students and staff. The software in these phones recorded contacts with other devices of same breed. In order to save battery life, each device was allowed to scan then area in every 5 minutes.

Sassy Dataset [19]: In this dataset, total of 27 T-mote invent devices were distributed among students and staff members in University of St Andrews. The experiments were conducted up to 79 days. The devices were programmed to generate beacons in every 6.67 seconds to detect other invent devices or base stations in 10m range. These devices recorded timestamps of contact duration and device IDs.

Table 4.2 Characteristics of data sets

Experimental data set	Cambridge	Reality	Sassy
Device	iMote	Phone	T-mote
Network type	Bluetooth	Bluetooth	IEEE 802.15.4 Sensors
Duration (days)	11	246	79
Scanning interval (seconds)	600	300	6.67
Number of Devices	54	97	27

4.4.2 Simulation Setup

This section gives the detail discussion on simulation setup and parameters used in synthetic and real mobility experiments.

4.4.2.1 Simulation Setup for Synthetic Experiments

The Opportunistic Networking Environment (ONE) [47] simulator is essentially designed to study the protocols used in opportunistic networks, thus an ideal choice for the evaluation of this algorithm (please see section 3.4.1 for details of ONE simulator). Table 4.3 summarizes the parameters used in this experiment.

Table 4.3 Parameters used in synthetic scenarios

Parameters	**Value**
World's size for Movement Model	10000 X 8000m
Total simulation time	57000s
No. of Hosts [pedestrians, buses]	[150, 10]=160
Message TTL (time to live)	960 mins
Time to move nodes in the world before real simulation commence	7200s
Nodes speed [pedestrians, buses]	[0.5-1.5, 7-10]m/s
Nodes pause time [pedestrians, cars, trams]	[0-0, 10-30]s
Message sizes	500KB-1MB
Message creation interval	15-25s
Air data transmit speed	250kbps
Transmit range	10m
Working day length	28800s
Probability to go shopping after work	0.5
Own car probability	0.5
Range of message source/destination addresses	0-159 nodes
Queue sizes	0,20,40,60,80,100,120,140,160,180 in MB
No. of each experiment runs	10

Devices considered in the simulations are Bluetooth enabled mobile phones or similar equipment, which are operating at 2Mbit/s data rate and air range of 10m. The activities of nodes consider in this simulation is for one day. The total length of the day lasts for 16 hours out of which 8 hours are considered as office working hours. After office work, probability of nodes to go out for evening activity is 0.5. Total number of nodes used in the simulation is ranged between 0-159, among these nodes some nodes act as source and rest as destination nodes. Nodes in simulation replicate as pedestrians and buses with the speed of 0.5-1.5 m/s and 10 m/s, respectively. Nodes can transmit varying length of messages between 500KB to 1MB, with the time interval of 15 to 25s.The nodes are simulated against different queue size length range between 0-180 MB with 20MB increment in each experiment.

4.4.2.2 Simulation Setup for Real Mobility traces Experiment

In order to test LOC algorithm in real mobility traces, we again used java based Opportunistic Networking Environment (ONE) simulator [47]. Table 4.4 summarises the parameters used in simulation. Total simulation time is equal to the final timestamp in respective datasets. Number of hosts present in simulation world is as per original number of participants. Varied length of message TTL used between 2 minutes to 3 weeks. In these experiments nodes speed is considered as per average speed of human. Transmission range of each node is 10 meters. The message queue size of each node is 12MB throughout the course of simulation. All nodes are participating as message sender/receiver.

Table 4.4 Parameters used in Real mobility scenarios

Parameters	**Value**
Total simulation time & No. of Hosts	As per dataset
Message TTL (time to live)	Varied [2mins – 3 weeks]
Nodes speed [pedestrians]	[0.5-1.5]m/s
Message sizes	500KB-1MB
Message creation interval	15-25s
Air data transmit speed	250kbps
Transmit range	10m
Movement Model	Map based
Range of message source/destination addresses	all nodes
Queue sizes	12MB
No. of each experiment runs	10

ONE simulator provides two types of classes to link external (real) mobility traces 1) ExternalMovementReader and 2) ExternalEventsQueue. The ExternalMovementReader class reads time stamped node locations from external mobility dataset and moves the node in the simulation accordingly. The two nodes in simulation environment exactly connect or disconnect as per recorded in real mobility dataset. The ExternalEventsQueue class can read events from the file and create number of messages and its size as per define in external message event file. ONE also provides another built-in message generation class known as MessageEventGenerator. This is a simple message generator class that creates uniformly distributed message creation patterns with configurable message creation interval, message size and source/destination host ranges. In these experiments, we used ExternalMovementReader class to read node movements from real mobility traces and MessageEventGenerator to create messages from ONE’s built-in message generation functionality.

4.5 Results

This section gives the detail discussion on results obtain from the experiments performed in both synthetic and real mobility traces.

4.5.1 Results of Synthetic Experiments

Sections 4.4.1.1 and 4.4.2.1 give the detail overview of scenario and simulation setup used for these experiments, respectively. To get the confidence interval, each time ten experiments were performed in WDM scenario using different seed values. For these experiments, 12 high performance multi-threading computers with 8 GB RAM is used. The performance of three opportunistic routing algorithms Epidemic, LI and LOC is evaluated against varying queue sizes. The different queue sizes help our study to gauge these algorithms at different scale because queue size affects the overall network performance. As queue size increases, more messages can be stored in nodes as a result number of message delivery increases at destinations. The results obtained from this simulation comprises of three metrics for performance evaluation, namely: Message delivery ratio, delay and cost or number of forwarded messages. Each graph contains three curves which represent three algorithms LOC, Epidemic and LI, respectively and these graphs are plotted against different queue sizes.

Figure 4.4 shows the average delivery ratio at destinations in WDM scenario. The graph shows that LOC outperforms both Epidemic and LI in terms of message delivery. As can be seen from graph, Epidemic has the poor performance because it relies on flooding and many packets drops, as a result of queue over-flow or time to live (TTL) of the messages expires due to not delivering in time. LI performance is much better than Epidemic because LI chooses forwarding nodes based on criteria: 1) popular nodes and 2) un-popular nodes with popular neighbours (high influential nodes). Although criteria used by LI indeed increases the delivery ratio but still many messages cannot be delivered due to unavailability of potential nodes that fulfil LI requirement. The reason of high message delivery in LOC algorithm is due to the directivity of messages towards destination nodes. These results prove that if nodes are aware of locations in opportunistic network then direction and distance from source to destination can be calculated using direction vector formulas. The messages are forwarded to only those nodes which are closer to the destinations in terms of direction and distance, thus achieve high directivity and as a result increase in overall delivery ratio.

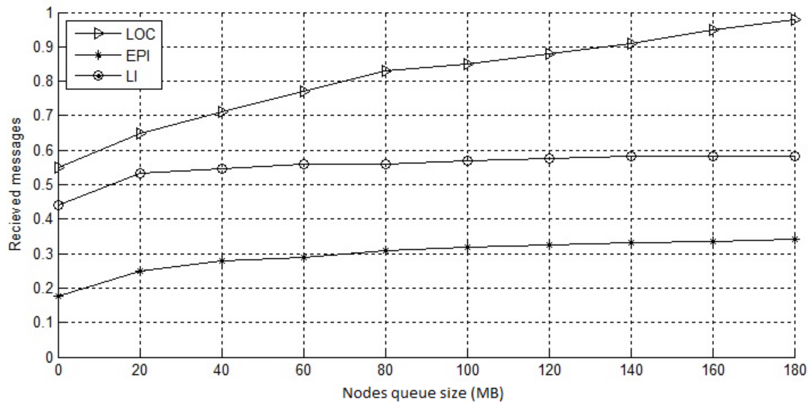


Figure 4.4 Average delivery ratio in WDM

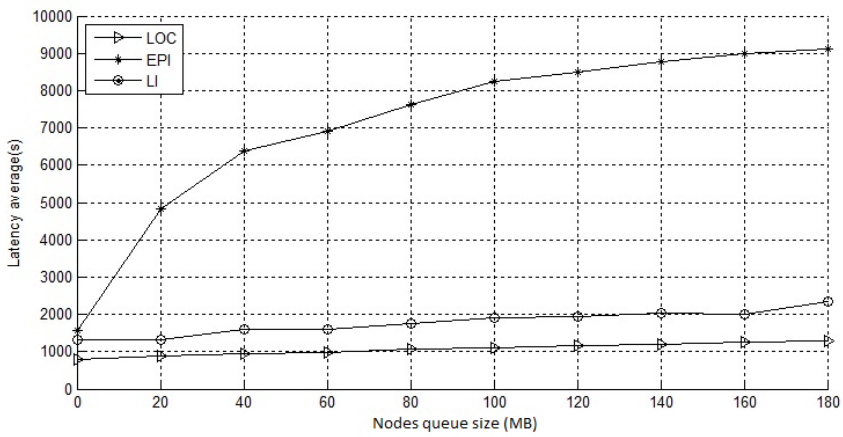


Figure 4.5 Average delay in WDM scenario

Figure 4.5 shows the average message delays experienced at destination nodes in WDM scenario. Epidemic algorithm shows the highest delays since nodes are accepting messages from any new node encounters without any criterion, thus exhausts their queues very quickly. Many irrelevant packets are queued; as a result many relevant messages are dropped. LI response is much better than Epidemic because LI uses criteria of exploiting popular or unpopular nodes with high connections, thus accommodating more relevant packets in queue. Due to LI selection criteria of choosing potential nodes, it keeps on forwarding the messages as a result has quickest response over Epidemic algorithm. LOC proves to be even faster than LI algorithm because nodes have knowledge of direction and distance towards destinations and nodes closer to the destinations are selected as forwarding nodes. LOC gives high directivity compare to LI as a result more speed achieved.

Figure 4.6 shows the average number of messages forwarded to intermediate nodes during the process of delivering messages to the destinations. Epidemic algorithm proves to be the most costly because it is forwarding messages to any node that comes in the way. The unnecessary flooding of messages can cause queues to over-flow quickly; in consequence many relevant messages may be dropped and as a result cost of this algorithm increases immensely. In contrast with Epidemic algorithm, LI proves to be less costly because LI forwards messages to only those nodes which fulfil its criteria. Only those nodes are considered as potential forwarding nodes which are popular or unpopular nodes with popular neighbours. However, LOC proves to be the most effective in terms of cost as compare to both Epidemic and LI algorithms. In LOC, first of all nodes are aware of their locations in the network, therefore it is easy to direct messages towards destinations. Only those nodes are considered as forwarding nodes which are closer to the destination nodes in terms of direction and distance.

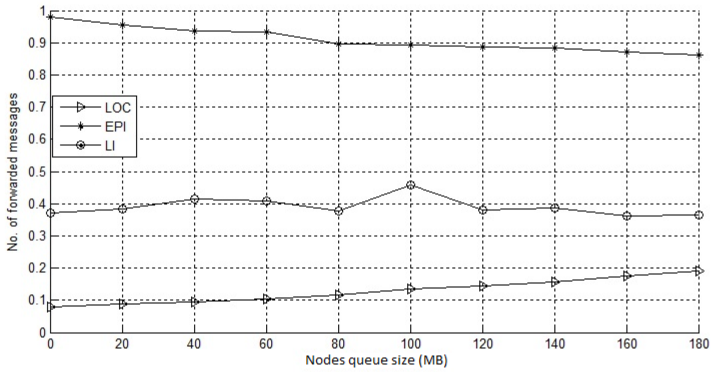


Figure 4.6 Average number of forwarded messages in WDM (normalised)

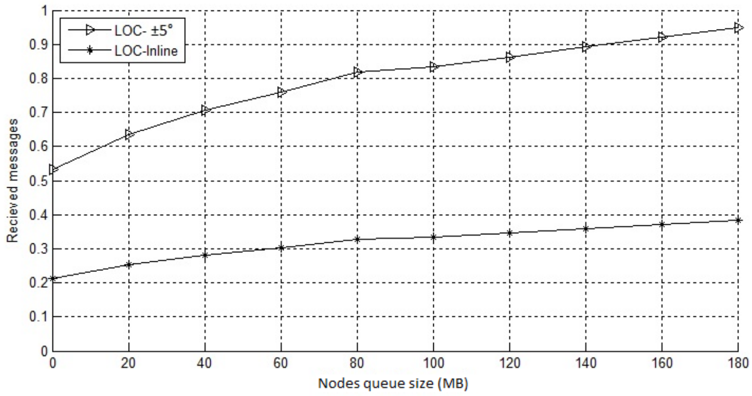


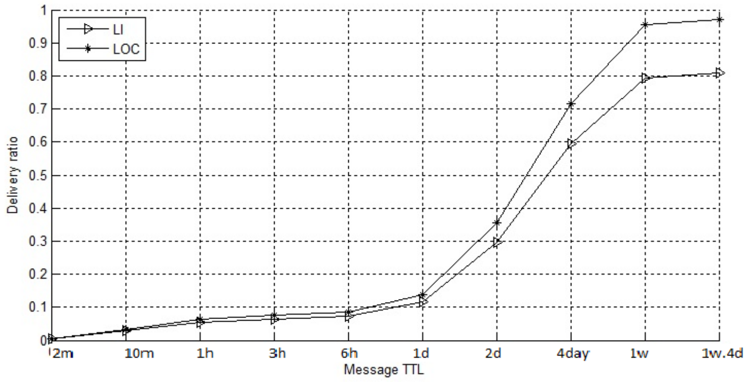
Figure 4.7 Message delivery ratio of LOC algorithm: ±5^0 VS Inline

Figure 4.7 shows the message delivery ratio using LOC algorithm by forwarding messages to "±5^0 versus inline" nodes. The result shows that LOC algorithm using ±5^0 difference has almost 40% improved delivery ratio over inline forwarding. In opportunistic network, very few nodes are available which are exactly inline in direction with original source and its destination node. Therefore, if LOC algorithm only forward messages to those nodes which are exactly inline then delivery ratio is low. However, if LOC algorithm is allowed to choose forwarding nodes which are present between ±5^0 from the reference direction (form between original source and its destination) then there is huge improvement in message delivery ratio. The reason of this improvement is because more nodes are available in the network for forwarding at the same time the algorithm ensures that directivity of messages should be towards their intended destinations.

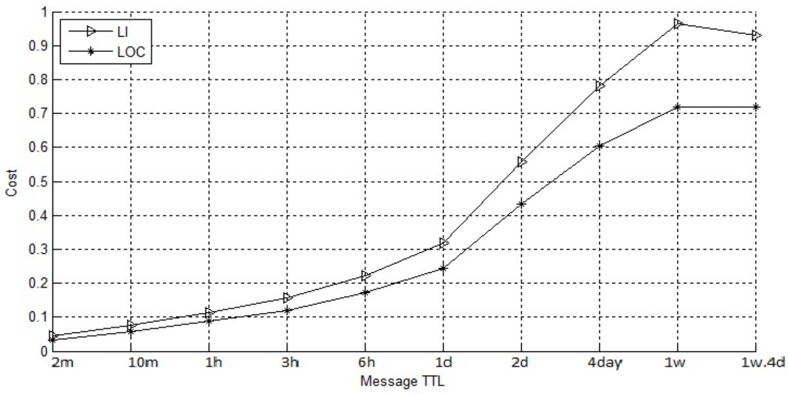
4.5.2 Results of Real Mobility Traces Experiments

Sections 4.4.1.2 and 4.4.2.2 give the detail overview of scenario and simulation setup used for these experiments, respectively. The graphs discussed in this section represents the performace of two algrithms LI and LOC. These algorithms are evaluated against varying duration of message TTL (time to live) in three datasets Cambridge, Reality and Sassy, respectively. The variation in message TTL help our study to assess algirthms on real datasets, which may comprise of days, weeks or even months. In these graphs, two metrics delivery ratio and cost or number of forwarded messages are plotted agains message TTL, respectively. Each graph contains two curves LI and LOC, respectively.

Figure 4.8 shows the average delivery ratio and delivery cost at destinations in Cambridge dataset. In Cambridge dataset, total simulation duration of simulaiton is equvalent to almost 11 days. The figure 4.8 (a) shows that LOC outperforms LI in terms of message delivery. As you can see from graph that LI performance is reduced due to its nature of forwarding decision. LI algorithm is based on the message forwarding criteria of choosing popular nodes or un-popular nodes with popular neighbours (high influential nodes). LI message delivery is restricted due to unavailability of potential nodes that can fulfill LI forwarding criteria. However, LOC shows better performance due to the awareness of destination node's location. The result shows that if approximate location of destinaion node is known then nodes which are closer to destination node interms of direction and distance, can be used as potential message forwarder. LOC selects potential message forwarder using directioanl vector formulas to achieve high directivity as a result overall delivery ratio is increased.



(a)

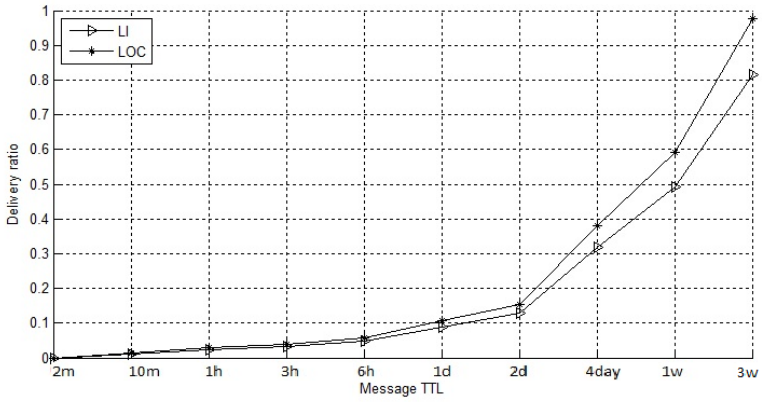


(b)

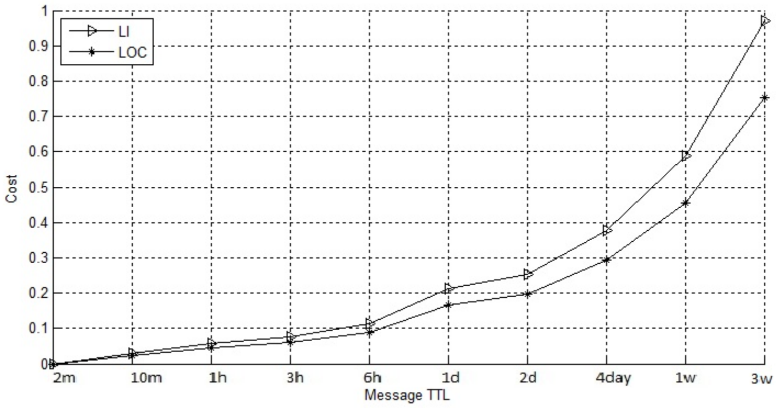
Figure 4.8 Performance of LOC in Cambridge dataset. (a) Average delivery ratio. (b) Delivery cost (normalised).

Figure 4.8(a) also show that when message time TTL set to be longer than 1 day and gradually increase in TTL duration, delivery ratio also start to increase at destination nodes. Figure 4.8(b) shows the normalised cost in Cambridge dataset. Graph shows that LOC has very low communication cost due to the more precise message directivity as compare to its counterpart LI. Fig 8.8 shows that LOC algorithm is much more cost effective in terms of high delivery ratio and low delivery cost.

Figure 4.9 shows the average delivery ratio and delivery cost at destinations in Reality dataset. Although, Reality dataset comprises of 9 months of information, but in this simulation we consider 3 weeks of information where the contact between nodes is highest. Fig 4.9(a) shows that LOC again proves to be the better algorithm than LI. This proves our assumption that if approximate location of destination node is known, using directional vector formulas, better message directivity can be achieved as a result overall message delivery increases. Fig 4.9(b) shows the delivery cost in Reality dataset. Again cost of message delivery in LOC algorithm is low due to better message directivity compare to LI algorithm. Fig 9 shows that LOC algorithm performance is better than LI in Reality dataset both in terms of delivery ratio and delivery cost.



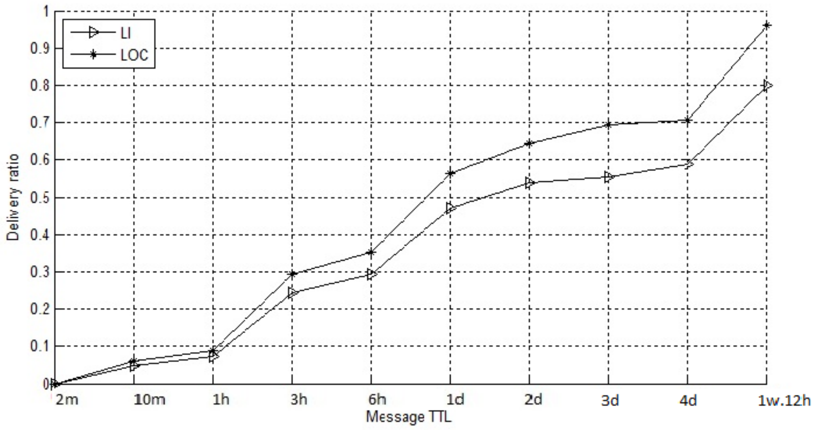
(a)



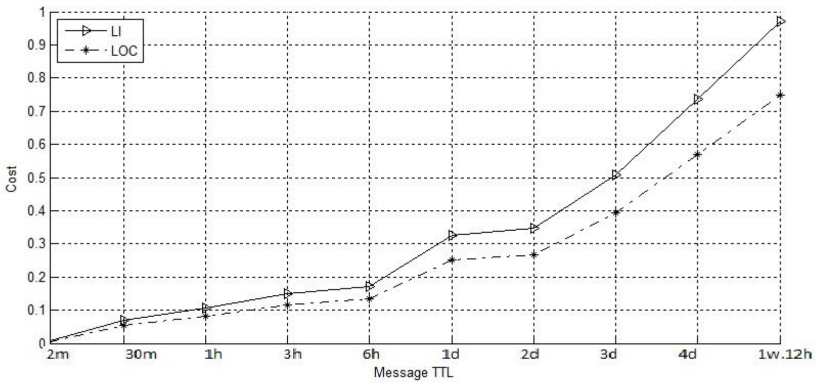
(b)

Figure 4.9 Performance of LOC in Reality dataset. (a) Average delivery ratio. (b) Delivery cost (normalised).

Figure 4.10 shows average delivery ratio and delivery cost in Sassy dataset. Sassy dataset contains 79 days of contact information. Figure 4.10(a) shows that message forwarding criteria used by LOC algorithm makes it far better in terms of delivery ratio as compare to LI algorithm in Sassy dataset. Also, figure 4.10(b) shows that LOC proves to be very cost effective in terms of delivery cost compare to LI algorithm.



(a)



(b)

Figure 4.10 Performance of LOC in Sassy dataset. (a) Average delivery ratio. (b) Delivery cost (normalised).

4.6 Chapter Summary

In opportunistic network, nodes do not have prior knowledge of routes. The major challenge in these networks is to deliver information to the intended recipient by keeping the communication cost minimum. In order to address these challenges, this chapter presented a new algorithm named as location aware content forwarding algorithm (LOC) using direction vectors. In LOC algorithm, source node is aware of its approximate destination position and its intended destination in the network by the help of Global Position System (GPS). The approximate position of source and intended destination node is used as reference values for intermediate nodes to direct messages towards intended destinations. The reference distance and direction values can be calculated from source to intended destinations by using direction vectors. The process of forwarding messages to intermediate nodes is very simple, forward messages to those nodes present closest to the reference values. By doing this, a great deal of message directivity is achieved.

Experimental results have confirmed that observation based on which the LOC algorithm performs message forwarding is turned out to be true. The new algorithm achieved great deal of message directivity by targeting only those nodes which are closer to the intended destinations in terms of direction and distance. LOC algorithm outperforms Lobby Influence in all aspects. LOC has not only shown significant improvement in message delivery ratio but also reduces communication cost successfully. LOC not only proved it robustness in synthetic movement models but also in real mobility traces.

Next chapter discusses the Bluetooth communication stack followed by literature review of single and multi-hope formation algorithms for Bluetooth technology.

Chapter 5

Implementation of ad-hoc and opportunistic routing in Bluetooth communication environment

This chapter discusses the proof of concept study that shows that the formation of piconet and scatternet can indeed achieve the single and multi-hop communication in Bluetooth environment. Also, an opportunistic forwarding technique is also tested in piconet and scatternet formation to observe its behaviour in this environment.

5.1 Introduction

Bluetooth is a short range radio technology that is present in almost every device i.e. laptops and smart phones as a built-in feature these days. The low-cost and low-power of Bluetooth technology makes it very useful for peer-to- peer ad hoc communication such as file sharing or personal area network (PAN) communication such as ear-piece connectivity with smart phones via Bluetooth technology. Bluetooth can also be used in situation such as conference room where a special announcement can be made to other Bluetooth-enabled devices via ad hoc network. Also, Bluetooth can be used as alternate ad hoc communication means in case of emergency or disaster where traditional communication means are not present.

Bluetooth based ad hoc network has special constraints compare to other wireless networks. For instance, Bluetooth technology by default works on master/slave principle known as piconet. A piconet consists of a master and maximum of up to seven slaves. Master node is the central entity in the network that is responsible for the communication of that piconet. If more than 8 nodes are present in the network then multiple piconet can be formed that can communicate each other by sharing slaves, this formation is known as scatternet (figure 5.1). The work presented by Miklos et al. [87] and Zurbes[88] show that if scatternet contains more piconets the rate of packet collision increases. Therefore, the performance of Bluetooth ad hoc network is greatly depends upon the efficiency of the formation of scatternet. Section 5.2 gives the detail literature review on state of the art algorithms for efficient formation of piconet and scatternets for single and multi-hop communication.

In Bluetooth communication environment a node may come across a single node or set of multiple nodes within 10m range. Therefore, this chapter presents a proof of concept study where opportunistic concept such as Bubble Rap [2] is tested in Bluetooth ad hoc networking environment. The notion behind this effort is to study the properties of these two networking environments, since opportunistic networks (one-to- one communication, where nodes do not have prior knowledge of destination nodes) are derived from ad hoc networks (one-to-many, where nodes have full or partial view of network).Thus, study of these two different environments yet related to each other may help us to find new ways of message forwarding in Bluetooth communication environment.

The purpose of these experiments is to learn and investigate the behaviour of nodes present in Bluetooth static and dynamic scatternet environment. In these experiments, two types of message transfer were performed 1) the traditional ad hoc communication from source to destination using AODV 2) opportunistic algorithm such as Bubble Rap (BR) concept on top of traditional ad hoc communication. In Bubble Rap [2], the concept of global and local ranking is proposed to transfer messages to that node which has higher social centrality ranking compare to the current node. Nodes with varying social ranking are allowed to join piconets and forward messages based on BR concept in scatternet environment. In BR algorithm, nodes forward messages to only those encountering nodes which are more popular than current node.

The rest of the chapter is organized as follows: Section 5.2 gives literature review of single and multi-hop scatternet formation algorithms. Section 5.3 highlights the objects behind this research. Section 5.4 provides details of network modelling that includes introduction of simulator used along with simulation setup and scenario used. Section 5.5 contains experimental results performed in static and dynamic scatternet environment. Section 5.6 concludes with the chapter summary.

5.2 Research Challenges

Unlike traditional ad hoc networks, source nodes do not have any partial or full view of network to establish reliable routes to their intended destinations in opportunistic networks. Nodes in opportunistic networks have to rely either on local information or information received from encountering node. Therefore, nodes in such unreliable environment have to rely on some forwarding criteria based on which they select suitable forwarding nodes. For instance, Bubble Rap [2] selects suitable forwarders based on the criteria of popularity such that if encountering node is more popular than current node, messages will be forwarded otherwise current node continues to look for suitable forwarders. Basically, in opportunistic networks, the aim of the researches is to find some suitable means to improve message delivery and reduce communication cost of the network.

In this research we are considering Bluetooth technology which has its own unique attributes compares to other wireless technologies. In Bluetooth communication environment, a pair of nodes form master/slave relationship in order to communicate each other, this formation is known as piconet. If more than 8 nodes are present, these nodes can communicate each other by establishing multiple piconets and this formation is known as scatternet. There has significant amount of research already been done on formation of piconet and scatternet in Bluetooth environment in order to achieve single or multi hop communication. Once the piconet or scatternet formation of nodes is achieved in the network then ad hoc routing algorithm such as AODV or DSDV can be used to form routes between source and destination nodes.

The motivation behind this piece of research is that in Bluetooth communication environment a node may come across a single node or set of multiple nodes within 10m range. The idea is not just rely on one-to-one opportunistic forwarding only instead if more than two nodes are present within 10m range one-to-multi hop communication can be achieved by forming piconet or scatternet. Therefore, the objective of this research is to find some means to improve overall message delivery and reduce communication cost by combining properties of opportunistic forwarding and traditional ad hoc routing algorithms. Thus, in order to prove this concept, this chapter presents network modelling and experimental results where opportunistic forwarding i.e. Bubble Rap is tested on top of traditional ad hoc network using AODV algorithm.

5.3 Literature Review

In a Bluetooth network, each pair of node communicating with each other must have the master-salve relationship; one has to take the role of master node and the other node has to become its slave. The slave node synchronizes its clock information to its master node for the transmission of data in same hopping mode. In a single piconet, there is one master node and a maximum of seven slaves. When more than seven nodes are required to connect, then one node might be used as bridge node and the overall formation of the network is known as scatternet. The role of a bridge node is to connect nodes belonging to different piconets and serve as a relay during the communication process between two nodes. In complex scatternet as shown in figure 5.1, a node may have a role of master in, at most, one piconet and can have role of slave in several other piconets at the same time.

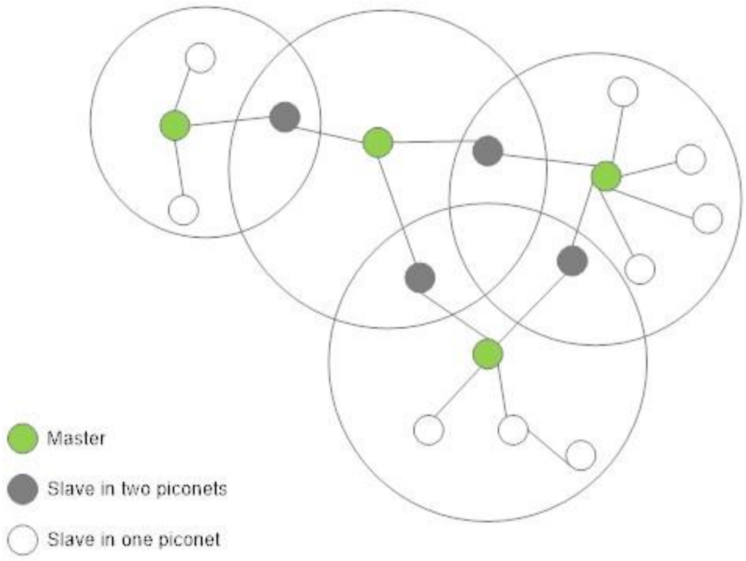


Figure 5. 1 Scatternet

A bridge node can provide services to a particular node on the basis of one node at a time. Suppose a bridge node is acting as a relay node and provides services to two nodes belonging to two different piconets and at the same time the master node calls that bridge node (acting as a slave in its own piconet). In such situation master node has to wait until its slave node (bridge node) completes its previous service. Such kind of communications, can cause longer delays and as a result the overall performance of the Bluetooth network can degrade significantly [52, 53].

The transmission delays in a Bluetooth network can be minimised, if problems related to scheduling transmission and time division for each master and slave node are synchronized with the overall operation of the network. [56, 57] discuss the importance of end-to-end transmission delays in inter-piconet traffic and emphasis on minimising delays in inter-piconet traffic rather than intra-piconet traffic. In inter-piconets, coordination is required between the bridge nodes for the allocation of particular slots known as rendezvous points

(RPs) [53], which are reserved for particular master-slave pairs. In large complex scatternets the coordination between bridge-nodes become very complex and require sophisticated mechanisms to establish RPs [58]. The characteristic of particular piconet or scatternets dictates the overall performance of scheduling protocols [54]. As discussed in [55], piconet switching has a great impact on overall performance of a network due to its large overhead. Therefore the overall performance of scatternets is not only dependant on the formation topology but also on the efficiency of the internal piconet switching and scheduling.

The following section will discuss different algorithms and protocols devised for the Bluetooth networks by different researchers. These algorithms and protocols are divided into two broad categories based on their nature of communications in Bluetooth Scatternets: single hop and multi-hop networks.

5.3.1 Single-hop Scatternets Algorithms

Single-hop scatternets are formed when all the Bluetooth nodes present in the area are within each other's range and may be called as a complete unit disk graph [54]. In single-hop scatternets, formation of network topology defines the efficiency of overall network. The algorithms devised for single-hop scatternet mainly deals with how efficient single-hop scatternet can be formed; for this purpose techniques use to address this issue includes traffic reduction, minimising delays, efficient utilization of piconets, parking and un-parking problems.

The importance of network capacity with regards to the formation of scatternets is discussed in [59]. In their work they highlighted the role of intrinsic capacity limitation in scatternets and showed that the capacity requirement can be reduced in scatternets but under the specific conditions. They discussed about formation of scatternets based on star and closed-loop topologies and demonstrated that the interference caused by inter-piconet transfer can effect on the choice of efficient Scatternet configurations.

In [60], an algorithm is presented that gathers information from its neighbours by using the inquiry process. The sender nodes scan the area by using random frequencies and nodes replay with the random back-off delay. In such kind of setup a node becomes the head node that is responsible for gathering information from its neighbouring nodes and assigning tasks to each node. Due to its centralized nature this algorithm is not scalable.

In [61], authors stress that due to the unique nature of Bluetooth technology in terms of connection limitation, a large network cannot be formed. They proposed a centralized algorithm that is applicable on conference scenarios. A head node is responsible to constantly scan other nodes using inquiry process same as [60] but with slight change; the topology constructed by head node is based on load metric rather than hop count. This algorithm must have the prior knowledge of nodes before moves into the construction phase of scatternet, in order to distribute traffic equally on different links to avoid congestion.

In [62, 63], a concept of *ring* is used for the formation of scatternet in single-hop networks. The algorithms use a centralized approach with park mode that causes extra delays in message transfer. The formation of such kind of network is very easy but when the diameter is very large, there could be many nodes participating in message transfer between two nodes, which causes extra delay.

A self-routing algorithm is proposed in [64] for Bluetooth networks. A tree like structure is used to organize nodes with Bluetooth IDs as keys. These keys will be used in the routing process for message transfer. This kind of scatternet formation causes extra communication cost in terms of the high traffic that is used to maintain the network. The main advantage is the maximum utilization of a piconet means all nodes in piconet are used to make relationship to their neighbouring nodes.

The algorithm used in [65] decreases the number of piconets and maintains connectivity and maximum node degree. The diameter of the network is very small, and as a result minimizes delay. The aim of this algorithm is to create loop opposite to tree like structure by keeping the scatternet size smaller and changing the master-slave relationship as per requirement of the situation, such as the merging of two scatternets into one. As a result the structure formed through this algorithm has a loop in the network and master nodes participating in the loop have additional slave nodes. The first step creates piconets with maximum of six nodes each. In the second step, one slave node is selected from each piconet and uses as bridge between piconets to reduce the diameter. Experimentally it is proved in [65] that this protocol works quite satisfactorily.

[66] proposed an algorithm that is specifically designed with low overhead for Bluetooth based ad-hoc and personal area networks. The algorithm proposed is based on the idea presented in [67], for multi-hop networks, where network is locally connected with degree limited and well-connected piconets with the exception of no parking nodes. Only 7 nodes

are allowed in a single piconet, no parking is allowed. A small overhead data is required to control and maintain the network and each node has to keep the information of only its one-hop neighbor node. In [66] authors apply the same concept as used in[67] but for single-hop networks, where the position of a node is not required in advance. Each node can have the information of neighbours during the neighbour detecting phase, present in its vicinity by using virtual information.

5.3.2 Multi-hop Scatternets Algorithms

A multi-hop scatternet is where two nodes are far from each other's communication range and a bridge node or nodes are used to make communication possible. The issues normally discussed in multi-hop scatternets algorithms are similar to those of single-hop scatternets algorithms, with the exception of large scale network.

A centralized approach is discussed in [68] for fixed Bluetooth sensor networks used in civil infrastructure such as highways and bridges. The idea presented in this approach is to consider network traffic generated by the sensor nodes and also take node's storage capacity as well as link strength into account while forming the network topology. This algorithm makes no assumptions with regards to deployment and location of nodes. The network formed through this approach is tree like in structure. The tree originates from the central point known as data logger. The data logger collects information from all the nodes present in the network, based on collected data it then can take decisions. The traffic send on link use the balance approach to avoid congestion.

An optimized concept is proposed in [69], where the idea is to minimize the network traffic load which is caused due to the changing network topology of scatternets. A problem of min-max creates bottlenecks in the network due to the congestion on a particular node. This problem can be dealt with if the network topology is built on the prior knowledge of traffic patterns and routes by using distributed approach.

An on demand routing protocol is proposed in [70] for the formation of scatternets, thus reducing the extra links and network maintenance traffic. In a typical Bluetooth network topology, all neighbours need to be discovered prior to sending the paging signal and route request. First the piconet is created and the role of master/salve is assigned before the route request packet is released. The neighbour nodes continue to search for the destination node. In proposed alternative topology formation methodology, the first alternative is to first create the full piconet and then release the route request. The second is to immediately release route request to each neighbour after paging, no need to wait for full establishment of piconet. The authors introduce another concept, an extended connectionless broadcast mechanism, where nodes in a same piconet use the same channel for communication. An inquiry message is broadcast on the channel by the master node and slaves keep listening on the same channels to grab the message. Such a process can minimize the route discovery delay considerably. The authors also suggest that if piconets in the network are synchronized this can remove the switching overhead and hence better utilization of channels. The method proposed is very good for real time traffic and in order to handle large packets in wireless networks.

A BlueStar formation for multi-hop scatternet is proposed in [71, 72]. The BlueStar formation is based on clustering scheme described in [73]. In BlueStar master node is selected on the basis of node weight rather than on node IDs. The master nodes are selected on the basis of weight and are called as *Clusterheads*. Each *Clusterhead* node becomes the master of its piconet and all other nodes present in that piconet become its slaves. The slave nodes present in Clusterhead's piconet may act as master nodes for other nodes thus forming their own piconets in tree like fashion. One drawback in [71]'s formation is degraded network performance that is due to the presence of more than seven slaves in a piconet. There is a traffic overhead and delay due to parked and un-parked process of slaves in order to communicate with their masters. Before clustering, a topology discovery process takes place for about eight seconds to gather the information about all neighbouring nodes.

In [74], a comparison of scatternet formation in Bluetooth networks using NS2 simulation is presented. The comparison is made on the formation techniques presented in [75, 76, and 77]. They conclude that the most time consuming process in Bluetooth network is device discovery, irrespective of any protocol used. The results also showed that Bluestar is the fastest protocol due to its simplicity for the formation of scatternets. One drawback in Bluestar is the presence of many slaves (more than seven) in a single piconet that can affect operations due to parking and un-parking of nodes.

A greedy centralized algorithm is proposed in [78], where a node keeps the information of others nodes that are at most 2-hops away. The 2-hops concept can be feasible in Bluetooth networks since neighbour nodes are known during the device discovery process. Each node is responsible to exchange the neighbourhood information so that they have a partial view of the network. In this algorithm, a piconet cannot have more than seven nodes. A node that has higher degree is elected as master node and can have seven slaves selected on the basis of least degree connections.

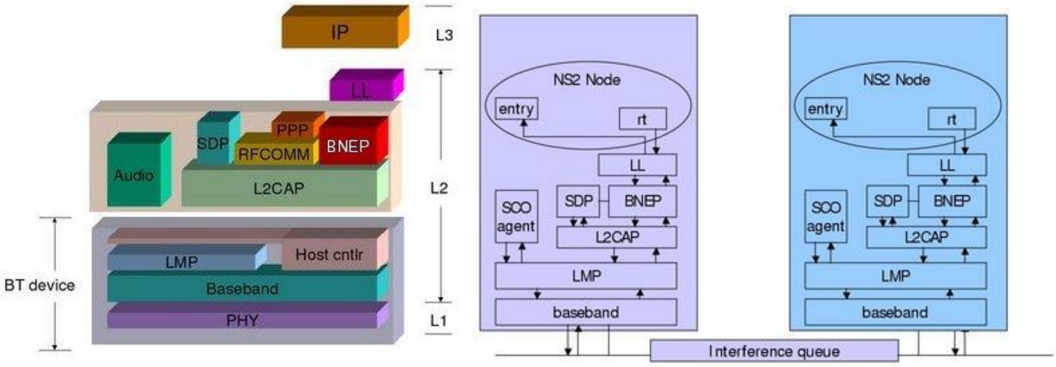
In [79, 80], a technique known as BlueMesh is used for the formation of scatternets. The proposed scheme assures network connectivity with limited number of slaves in each piconet. A two phase discovery process is used to gather the information about the neighboring nodes at most 2-hops away. A modified clustering is used, where if a piconet has more than seven nodes, the master node will select seven slaves and allows its slaves to form relationships with the remaining nodes present in that piconet. In this way the master node can have access to the remaining nodes. The same concept is proved in [81] with five slaves. The scatternet formation is based on the repetition process. At the start no node has been assigned the task of either master or slave. The selection of master node (could be more than one) is based on the largest weighted node among nodes present in the area. In the next repetition the original masters do not participate in the selection process because they have already made piconets with their salves, however slave nodes and remaining undecided nodes again participate and the same process goes on until all nodes become part of their respective piconets. Simulation results showed that although this algorithm may show some weaknesses on some other metrics, but where position information is not used, it is the best algorithm available.

5.4 Network Modelling

This section gives an overview of the simulator used for the purpose of this piece of research. Furthermore, this section also discusses various scenarios with simulation parameter used in these experiments.

5.4.1 Simulator

A UCBT-Bluetooth (stands for University of Cincinnati – BlueTooth) extension for NS-2 simulator [20] is used for simulation. UCBT-Bluetooth is NS-2 based Bluetooth network module which works on principle of Bluetooth protocol specification version 1.1 and partially version 2. UCBT can simulate most of the specification at Baseband and above like link management protocol (LMP), logical link control and adaption protocol (L2CAP), Bluetooth network encapsulation protocol (BNEP) as shown in figure 5.2. UCBT can also perform device discovery, connection set up, frequency hopping, Hold, Sniff and Park modes management. UCBT also allows nodes to form piconets and there is provision in this simulator to establish communication between two multiple piconets with the help of slave nodes known as “bridge nodes”.



Bluetooth Stack BTNode

Figure 5.2 Bluetooth Stack & NS2-BTNode [20]

Bluetooth supports two type of services Synchronous Connection Oriented (SCO) and Asynchronous Connectionless Links (ACL) with the characteristics of circuit switched and packet switched network, respectively. The SCO links are designed to deal with real-time traffic such as voice, where it uses slot reservation for specific period of length, thus allows guaranteed delay and bandwidth. The drawback of SCO is that it can only support fixed maximum bandwidth of up 64kb/s, which is not compatible with real time or delay sensitive applications such as audio and video streaming where variable and asymmetric traffic is required. The ACL link is designed to support data application with varying delay. ACL can support both symmetric and asymmetric bandwidth with Forward Error Correction (FEC) and retransmission mechanism. When there are more than two nodes in a piconet, then master node has to rely on polling algorithm to allocate time slots between slave nodes thus requires ACL type of links. For the reasons just discussed, these experiments will consider only ACL type of traffic.

For simulation purposes all nodes are set to be within 10 meters range. The scatternet formation is achieved using the algorithm proposed by Ching law in [16]. In order to perform these experiments the NS-2 code has been adapted to use social centrality levels of nodes which is used as an input parameter and can be changed to different values to give different levels of ranks to the node. An additional output parameter for battery life and three other inbuilt parameters, delay, data rates and delivery ratio, are also used.

5.4.2 Static Scatternet Environment

Two varying length of scenarios are considered for the detail study of these experiments named as Static scatternet in piconet scenario and Static scatternet in multi-piconet scenario with 8 and 32 nodes respectively. Each scenario explains its network topology along with experimental parameters.

5.4.2.1) Static scatternet in piconet scenario

For these experiments, up to six different connections are considered from one simultaneous connection to six simultaneous connections in a single piconet. Under these experiments different behaviours such as data rate, delay, delivery ratio and energy consumption is studied on different nodes. Fig. 5.3 shows the network topology of the single piconet, total 8 nodes are used where node ‘0’ is acting as a master node and remaining nodes are its slaves. For BR experiments each node has assigned a social ranking value, which defines its social status (popularity) in the community. Table 5.1 shows the list of parameters considered for these experiments. Section 5.5.1 discusses the experimental results based on scenario and experimental parameters describe in this section.

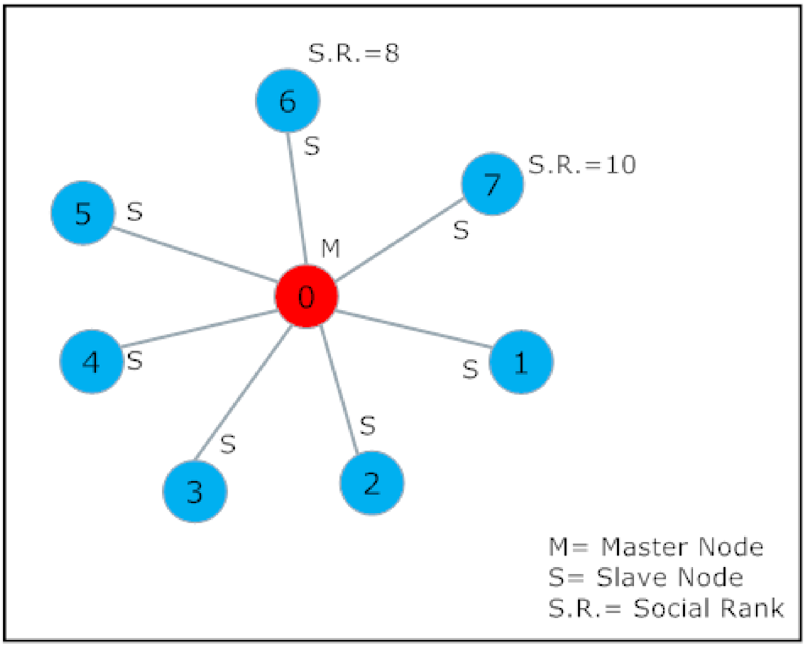


Figure 5.3 Network topology for single piconet

Table 5.1 Simulation Parameters for Single Piconet

Sr. No.	Parameters	Value
1.	No. of nodes	08
2.	Area (range)	10 m
3.	No. of slaves (per piconet)	07
4.	Routing Protocol	AODV
5.	Scheduling (or Polling) algorithm	PRR
6.	Traffic Sources	06
7.	Packet Type	UDP
8.	Packet Size	1400
9.	Interval	0.015
10.	Bluetooth Baseband packet type	DH3
11.	Battery Life (initial)	10 J
12.	Avg. energy consumption rate	2.5e-3 J
13.	Min. Energy	0.1 J
14.	Node Rank (social popularity level)	Default = 01, Node(7)=10, Node(6)=8,
15.	No. of times each experiment run	20

5.4.2.2) Static scatternet in multi-piconet scenario

For these experiments, up to five different connections are considered from one simultaneous connection to five simultaneous connections in scatternet where source nodes are in piconet ‘1’ and destination nodes are in piconet ‘4’. In order to specifically understand the BR concept two source nodes are considered from piconet ‘2’, which are destined for the highest ranked nodes in the network. Total 32 nodes are considered in these experiments, the network topology is depicted in figure 5.4. The simulation parameters considered for this scenario is almost similar to the section 5.4.2.1 with the addition of bridge algorithm that is used for the communication between two piconets. In order to simplify our experiments, nodes are allowed to join maximum of up to 2 piconets. Under these experiments different behavior such as data rate, delay, delivery ratio and energy consumption is studied on different nodes. For BR experiments each node has assigned a social ranking value, which defines its social status (popularity) in the community. Table 5.2 shows the list of parameters considered for these experiments. Section 5.5.2 discusses the experimental results based on scenario and experimental parameters describe in this section.

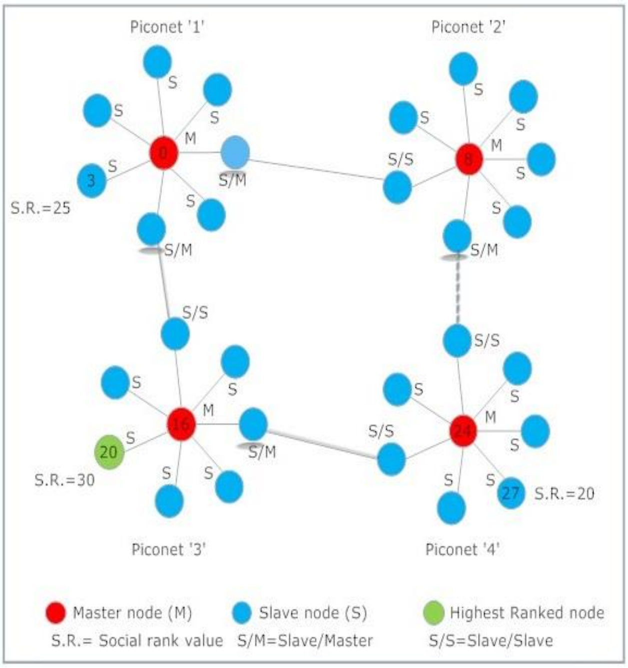


Figure 5. 4 Network topology for 32-nodes scatternet

Table 5. 2 Simulation Parameters for Scatternet

Sr. No.	Parameters	Value
1.	No. of nodes	32
2.	Area (range)	10 m
3.	Max. allowable slaves (per piconet)	07
4.	Routing Protocol	AODV
5.	Scheduling (or Polling) algorithm	PRR
6.	Bridge Algorithm	TDRP
7.	Traffic Sources	07
8.	Packet Type	UDP
9.	Packet Size	1400
10.	Interval	0.015
11.	Bluetooth Baseband packet type	DH3
12.	Battery Life (initial)	10 J
13.	Avg. energy consumption rate	2.5e-3 J
14.	Min. Energy	0.1 J
15.	Node Rank (social popularity level)	Default = 01, Node(20)=30 Node(27)=20, Node(3)=25,
16.	No. of times each experiment run	20

5.4.3 Dynamic Scatternet Environment

In this section, different experiments have performed in order to study the behaviour of nodes in dynamic scatternet conditions. In these experiments, nodes are allowed to join or leave piconets and record the effect of node's mobility in terms of data rates, delay, delivery ratio and energy consumption (only for Bubble Rap algorithm). In these experiments, same experiment and simulator settings are used which were used previously in static scatternet experiments with minor changes to adapt these experiments for dynamic conditions.

Table 5.3 Simulation Parameters for Dynamic Scatternet

Sr. No.	Parameters	Value
1.	No. of nodes	29
2.	Area (range)	20x20m
3.	Max. allowable slaves (per piconet)	07
4.	Routing Protocol	AODV
5.	Scheduling (or Polling) algorithm	PRR
6.	Bridge Algorithm	TDRP
7	Packet Type	UDP
8.	Packet Size	1400
9..	Interval	0.015
10.	Bluetooth Baseband packet type	DH5
11.	Battery Life (initial)	10 J
12.	Avg. energy consumption rate	2.5e-3 J
13.	Min. Energy	0.1 J
14.	Node Rank (social popularity level)	Default = 01, Node(12)=100 Node(22)=200, Node(26)=1000
15.	No. of times each experiment run	30

Three different set of scenarios are considered for the detail study of these experiments named as scenario dynamic scatternet in mobile source scenario, dynamic scatternet in mobile destination scenario and dynamic scatternet in mobile High Ranked (H.R.) scenario . Each scenario explains its network topology and graphs whereas experimental parameters consider for each scenario is similar, as listed in table 5.3.

5.4.3.1) Dynamic scatternet in mobile source scenario

In this experiment, a source node is allowed to join and leave a particular piconet at specific period of time as depicted in figure 5.5. To understand the effect of source node mobility in Bluetooth scatternet, different behavior such as data rates, delay and delivery ratio is recorded at destination node and graphs are drawn against these values, which will be discussed shortly. For BR experiment, each node has assigned a social ranking value, which defines its social status (popularity) in the community. By default each node has social rank of '1', but some node has given higher rank which makes them more popular among other nodes as shown in figure 5.5. Section 5.5.3 discusses the experimental results based on scenario and experimental parameters describe in this section.

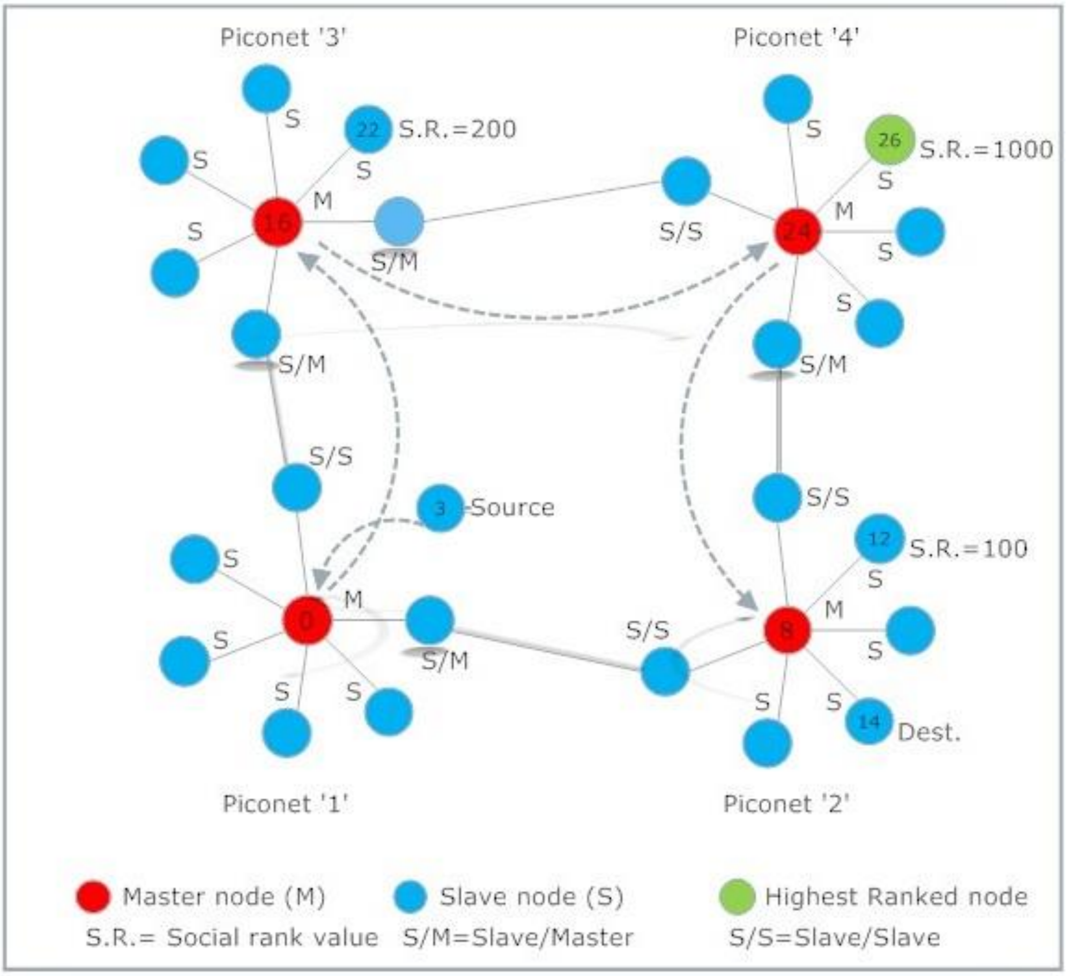


Figure 5.5 Network topology for source node movement in scatternet

5.4.3.2) Dynamic scatternet in mobile destination scenario

The simulation parameters used in this experiment are similar to the section 5.4.2.2. However, source node is static and destination node is allowed to leave or join any piconet and can move freely with in scatternet as shown in figure 5.6. To understand the effect of destination node mobility in Bluetooth scatternet, different behavior such as data rates, delay and delivery ratio is recorded at destination node and graphs are drawn against these value. For BR experiment, each node has assigned a social ranking value, which defines its social status (popularity) in the community. By default each node has social rank of ‘1’, but some node has given higher rank which makes them more popular among other nodes as shown in figure 5.6. Section 5.5.4 discusses the experimental results based on scenario and experimental parameters describe in this section.

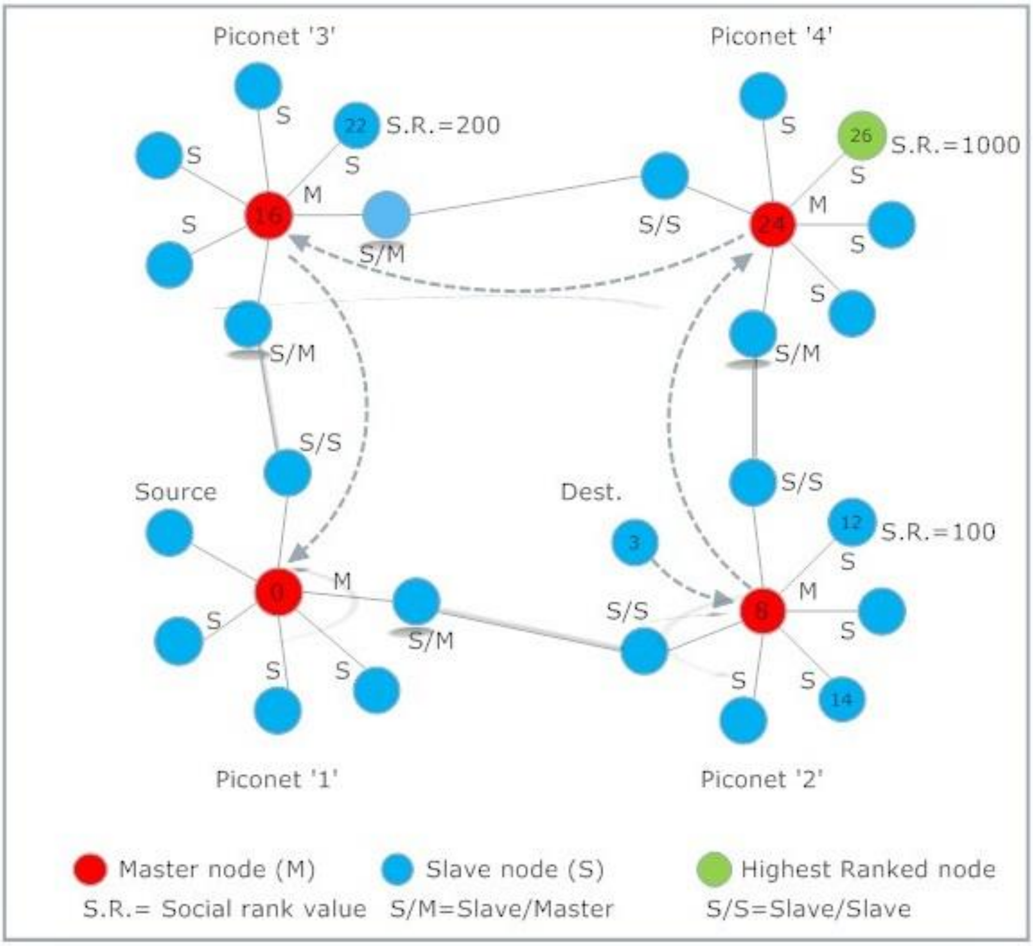


Figure 5.6 Network topology for destination node movement in scatternet

5.4.3.3) Dynamic scatternet in mobile H.R. scenario

The simulation parameters used in this experiment is similar to that of section 5.4.2.2. The purpose of this experiment is to further investigate BR-based scatternet communication environment by allowing most popular (highest ranked) nodes to move freely. By default each node has assigned social rank of ‘1’, among these nodes three nodes are chosen as most popular nodes with social ranking of 1000, 200 and 100 and named (based on their ranking) as 1HR, 2HR and 3HR, respectively, as shown in figure 5.7. Since this experiment is to specifically investigate effect of highest ranked nodes movement, so destination nodes are not present in the network, in this way source node present in piconet '1' will seek most popular nodes to transmit messages. To understand the effect of HR (Highest Ranked) nodes mobility in Bluetooth scatternet, different behaviour such as data rates, delay, delivery ratio and energy consumption is recorded at HR nodes and graphs are drawn against these values. Section 5.5.5 discusses the experimental results based on scenario and experimental parameters describe in this section.

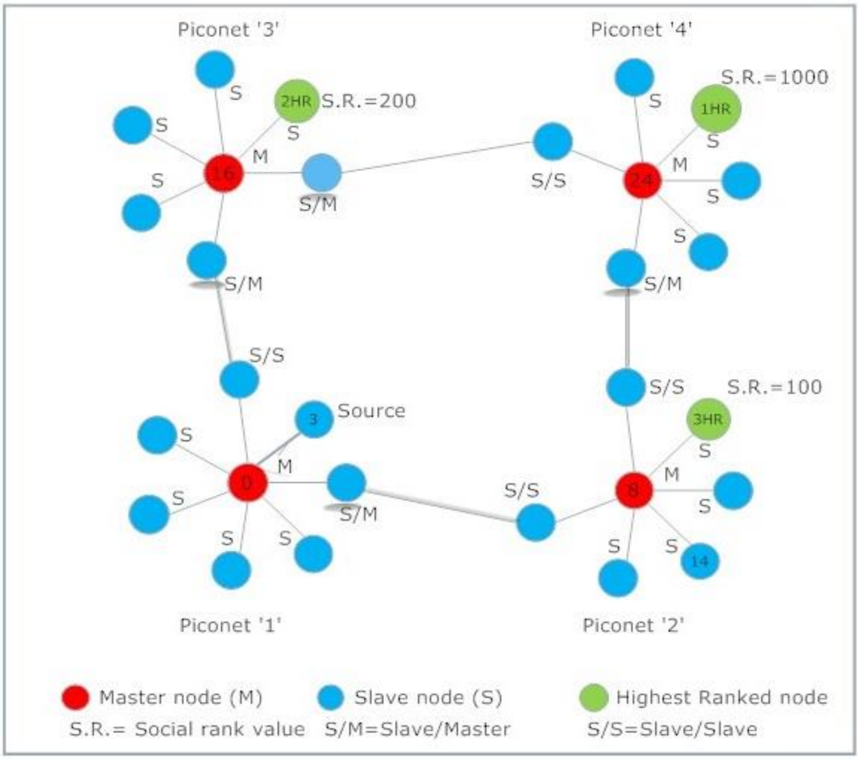


Figure 5.7 Network topology for H.R. nodes movement in scatternet

5.5 Results

This section provides comparison graphs along with its detail discussion on experiments performed in different scenarios.

5.5.1 Results of static scatternet in piconet scenario

The experimental results presented in this section are based on experimental parameters and scenario discussed in section 5.4.2.1.

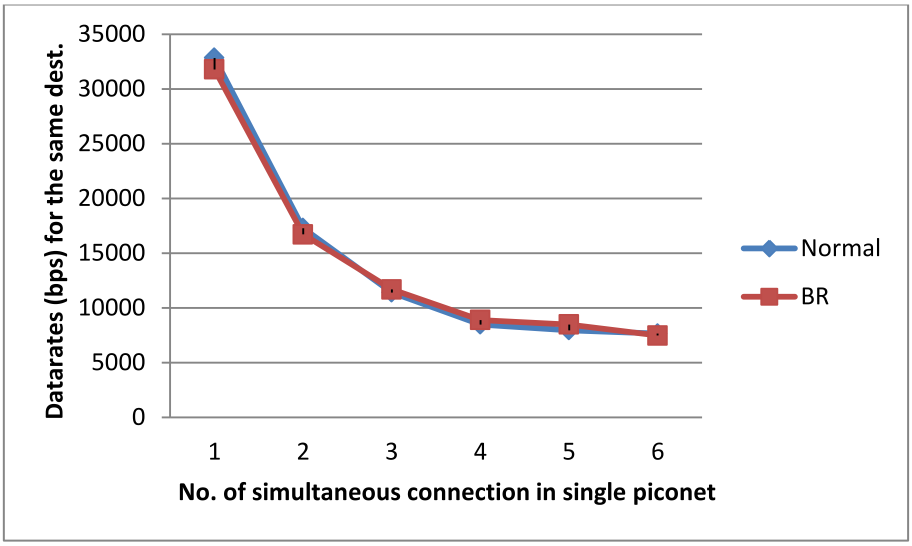


Figure 5.8 Data rates for the same destination in single piconet

Fig. 5.8 shows the data rate response in bits per second for the same destination as number of simultaneous connections increase in the single piconet. As it's evident in the graph that when there is only one connection present in the piconet the data rate received at the destination is highest. As numbers of simultaneous connections increase in the piconet the data rate received at the destination shows the decreasing trend. This is because the master node is the central entity of a piconet which is responsible to maintain the order in the piconet. When there is more than one slave node, master node has to schedule and distribute time slots among its slave and restrict each node to transmit data to its specified time interval only. This is the reason when no. of connections in piconet is 6, destination gets lowest data rate. The same trend is also shown by the BR algorithm surprisingly it is behaving similar like normal curve as shown in graph. This shows that the behavior of BR algorithm is almost similar if the destination is present in the scatternet. Later graphs will show that the BR algorithm only comes into the play when the destination is not present in the network or the link between source piconet to the destination piconet is broken.

Fig. 5.9 shows the delay response of the same destination with the increasing number of nodes connections in a single piconet. When there is only one connection active in the piconet the minimum delay is observed at the destination. As the number of simultaneous connections increase in the network the more delay will be observed at the destination. However, if we look at the figure the maximum delay observed when numbers of simultaneous connections are 3 and after that increase in the number of simultaneous connections has little impact on the delay, almost constant (stays at 2 seconds) with small down trend. The reason behind this behaviour is due to the fact that master node is responsible for the time allocation among its slave nodes, for this purpose it uses a schedule or polling algorithm, which is responsible for the fair distribution of time slots. Since this experiment uses PRR [82] scheduled algorithm, the characteristic of this algorithm is to distribute time slots based on priority in round robin fashion. So when there is only one connection the whole time is allocated to the only one node, however as number of connection increase above 2 simultaneous connections the time distribution almost become equal, thus cases the delay with little variation as shown in graph. Several polling algorithms [52, 53, 56, 57] have been designed for the scheduling of time slots in piconet, this experiment also showed that better scheduling algorithm has great impact in Bluetooth communication. The destination node is present in the piconet so behaviour of BR algorithm is almost similar to the normal communication.

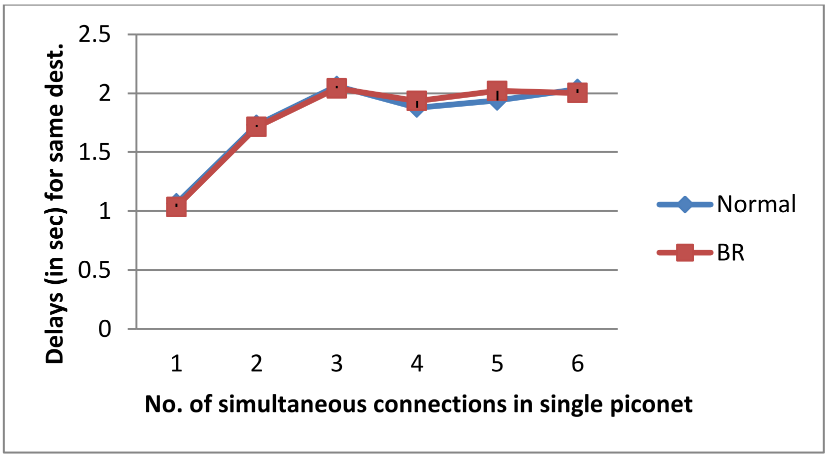


Figure 5.9 Delay responses for the same destination in single piconet

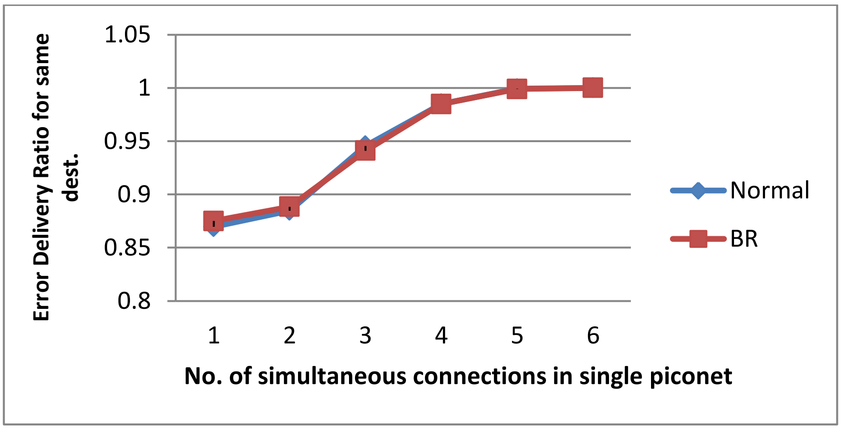


Figure 5.10 Packet delivery ratio for the same destination in single piconet

Fig. 5.10 shows the packet error delivery ratio for the same destination node in piconet. Both BR and normal communication shows the same trend. Graph indicates that when there is only one connection the error is low, as the number of simultaneous connections increase in the piconet the error gets increased and touches to 1 when there are 6 simultaneous connections active in the piconet. The reason behind this trend is that when there is only one connection in piconet the maximum time is allocated to only one node as a result the node can transfer data at higher rates as indicated in fig. 5.8. When node sends the data at higher rate there is less probability of error during the transmission due to large bulk of data. As number of simultaneous connection increases in the piconet, master node has to use the polling algorithm to equally distribute the time slots among its slaves as a result each salve node will get a limited amount of time slots for data transmission, thus error delivery ratio is higher.

As it is shown in previous graphs the behaviour of BR algorithm is similar to the normal communication in piconet, if destination is present in the network. Based on previous facts Fig. 5.11 only considers the normal communication as we are confident that BR algorithm would have shown the similar results. Fig. 5.11 explains the data rates received at each node by the end of simulation when there were 6 simultaneous connections in the piconet. As explained earlier that master node is the central entity of a piconet which is responsible for the time distribution among slave nodes. Other than node ‘0’ each node received almost same level of data rates, the reason behind this behaviours is that node ‘1’ to node ‘6’ are all slave nodes whereas node ‘0’ is the master node. The master node is scheduling the time slots into equal slices as a result each node is getting fair amount of equal data rates. However this graph also reveal that the maximum data rate will be received by the master node because in a piconet there is no direct communication between slave nodes they have to rely on master node (node ‘0’) in order to communicate with the other node in the same piconet. For this reason each node will transmit its data via master node thus master node will receive the data rate which is equal to the combine sum of all data rates send by the slave nodes.

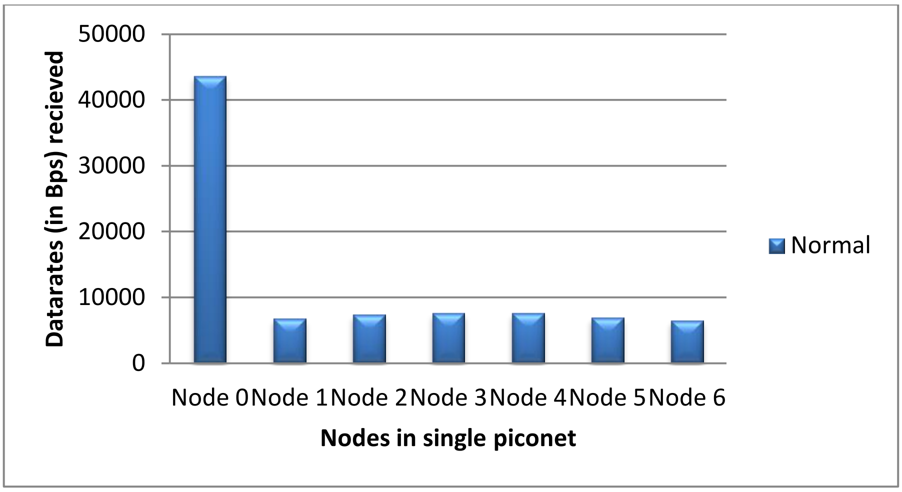


Figure 5.11Data rates received at different nodes

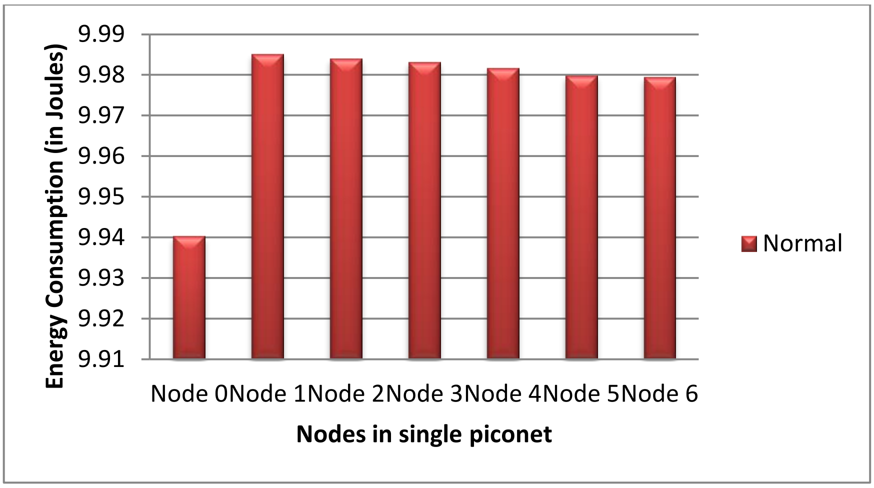


Figure 5.12 Energy consumption in single piconet

Fig. 5.12 shows the typical energy consumption of different nodes as the number of simultaneous connections in piconet is 6. The communication among nodes is considered as normal, since previous results indicated that if destination is present in the network BR algorithm based piconet will show exactly the same behaviour as does by the normal communication in piconet. Energy consumption among slave nodes (node ‘1’ to node ‘6’) is almost equal or has little variation. However, node ‘0’ which is the master node of the piconet shows the major drop in battery life. The reason behind such drop is due to the fact that master node is responsible for the piconet, not only its energy is used for the time scheduling for its slave node also it is being used as a bridge node or forwarding node for each of the slave node. Hence much of energy in master node (node ‘0’) is utilized in storing and forwarding the messages as well as time scheduling.

So far all graphs of BR-based piconet have shown the similar results as shown by the normal communication in piconets. However, fig. 5.13 shows the typical behaviour of nodes in BR-based piconet. The experiments showed that BR algorithm only comes into play when destination is not present in the piconet, if destination is present in the piconet BR will exactly behave like normal communication in piconet. So, in order to make BR algorithm comes into play, the destinations considered is not present in the piconet. In this experiment, node '7' has assigned social rank of 10; node '6' has assigned social rank of 8 and all remaining nodes have assigned social rank of 1. When source node finds that the destination is not present in the piconet then it will rely on BR algorithm and start sending data to the high ranked node. Since in piconet a node with rank 8 is also present but nodes always seek for highest ranked (centrality) node based on BR concept so they will send data to the node '7' which has highest ranked among all nodes i.e. 10. Fig. 5.13 shows that when there is only one source present in the piconet then data rates received at node '7' and node '0' (master node) has almost same because whatever master node receives from the source node it will forward it to the highest ranked node. But we can see that when there is more than one simultaneous connection which sends data then master node has to start scheduling time among slave nodes, although master node is receiving data from different nodes but it will forward data to the highest ranked node only in its allotted time. So when there are 6 simultaneous connections master node has to distribute time slots equally among slaves node so data rate receive at highest central node is minimum.

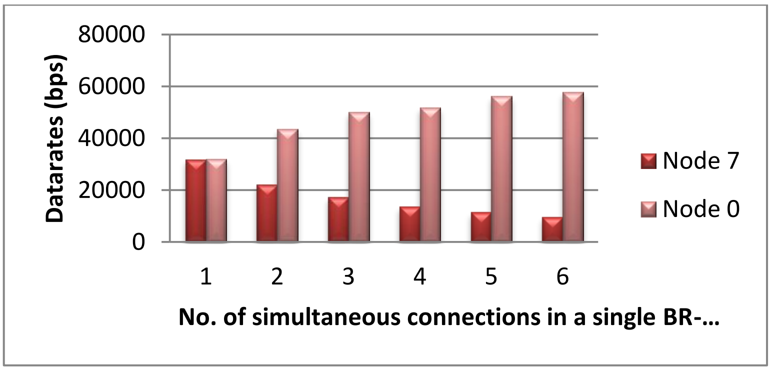


Figure 5.13 Data rates received at highest ranked node and master node in BR-based piconet

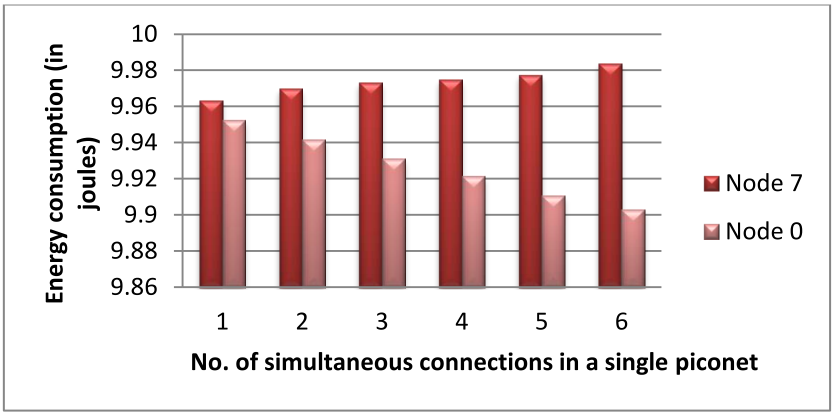


Figure 5.14 Energy consumption in highest ranked node and master node in BR-based piconet

Fig. 5.14 shows the energy consumption of nodes in BR-based piconet. Same setting is considered for the BR-based piconet as discussed earlier. As graph shows that when there is only one connection active the energy consumption of node '0' (master node) is slightly higher than the highest ranked node. This is due to the fact that master node is acting as a forwarding node, first it receive data from source node and then transmit it to the highest central node thus performing the double job. The graph also indicates that as number of simultaneous connections increase in the piconet the battery consumption of master node will schedule the time slots among slave nodes. Whereas graph also indicates that as connections are increasing the energy consumption of highest ranked node is getting lesser this is because more nodes are getting active so time slot of highest ranked node is starting to shrink as a result it is getting less data thus over all energy consumption is lower.

5.5.2) Results of static scatternet in multi-piconet scenario

The experimental results presented in this section are based on experimental parameters and scenario discussed in section 5.4.2.2.

Fig. 5.15 & Fig. 5.16 shows the data rate response in bits per second for the same destination in scatternet environment as the number of simultaneous connections increases from one simultaneous connection up to five simultaneous connections. Two different set of experiments are performed in order to check the data rate response for the same destination in presence of one and two routes, as depicted in Fig. 5.15 and Fig. 5.16 respectively. The simulation parameters considered for both types of experiments are exactly the same. It is clearly shown in the figures that when there is only one connection present between source piconet ‘1’ and destination piconet ‘4’ the data rate response is maximum and it starts to decrease as number of simultaneous connections increase in scatternet. Figures show that behaviour of normal and BR-based scatternet is almost similar in the presence of single and double paths, this is due to the fact that BR performs in a similar fashion as normal scatternet perform as long as destination node is present in the scatternet, if destination node is not present in the scatternet than BR-based scatternet will perform differently, which is discussed in upcoming graphs. If we compare data rate response of Fig. 5.8 with Fig. 5.15 there is a clear difference, Fig. 5.8 shows the higher data rate response whereas Fig. 5.15 shows the low data rate response in scatternet environment. This is because Fig 5.8 deals with the single piconet where one master node is present in the network and there is no bridge node, therefore time scheduling is very simple, less delays as a result higher data rates. Whereas, Fig. 5.15 deals with scatternet where more than one piconet and also bridge nodes are present in the network, therefore the time scheduling in scatternet is complex which results in higher delays, higher error delivery ratio and low data rates. When we compare Fig. 5.15 with Fig 5.16 it is quite evident that if more than one path is available from source node to destination node in scatternet the data rates received at the destination is higher. Therefore it is proved from the experiments that if number of bridge nodes increase in the network there will be more chances of having multiple routes from source node to the destination node which will increase the data rates in Bluetooth nodes in static scatternet environment.

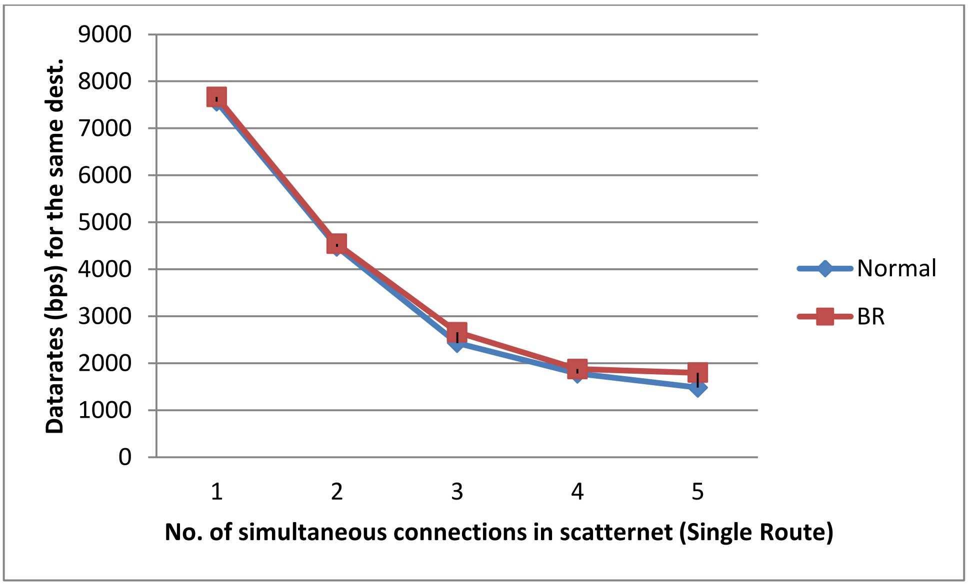


Figure 5.15 Data rates for the same destination in scatternet with single route

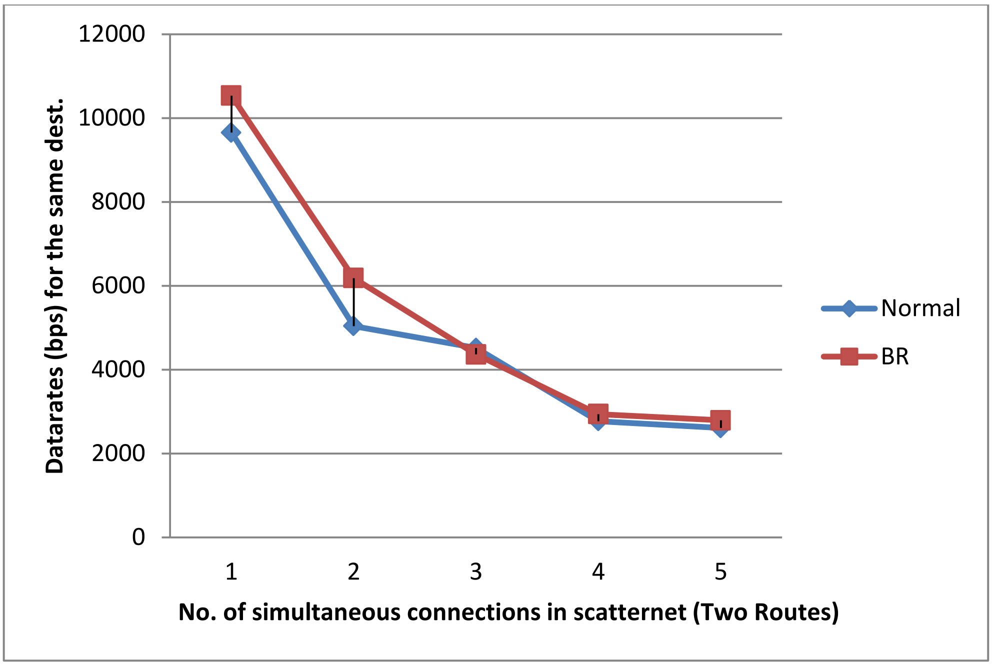


Figure 5.16 Data rates for the same destination in scatternet with two routes

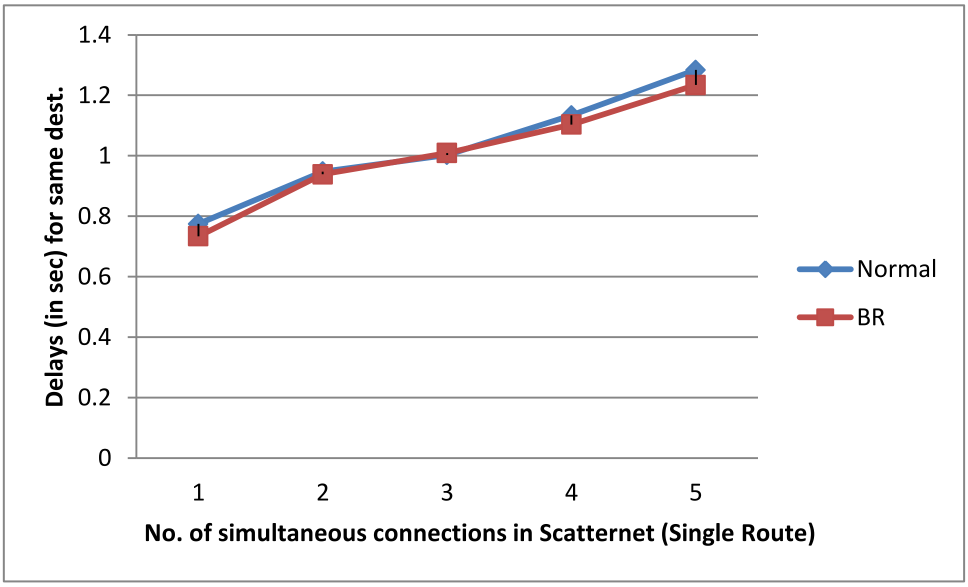


Figure 5.17 Delay response for same destination with single route

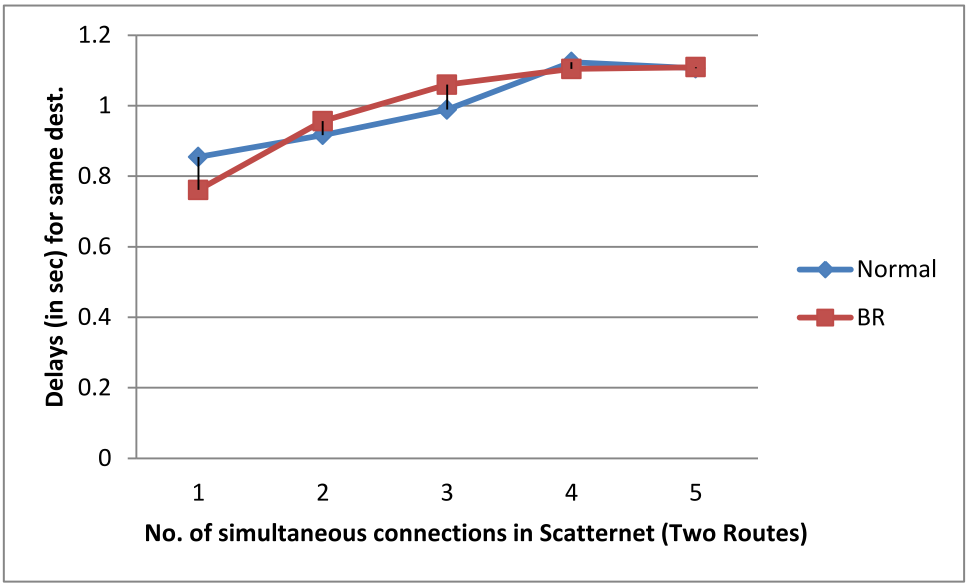


Figure 5.18 Delay response for same destination with two routes

Fig. 5.17 & Fig. 5.18 show the delay response of the same destination with the increasing number of simultaneous connections in scatternet using single and two routes respectively. When there is only one connection active between piconet ‘1’ and piconet ‘4’ the minimum delay is observed at the destination. As number of simultaneous connections increase in the network more delay is observed at the destination. As it is also evident in the figures that there is variation in graph this is due to the fact that time scheduling is not only happen in piconets but also bridge nodes are involved in the network so each piconet has its own time offset based on the scheduled algorithm used in the piconet along with the bridge algorithm for the salve node participating in two piconets, so each node can only transmit in its own schedule time and same is true for the bridge node that it can only communicate in its dedicated time slot, thus causes varying delays. The BR-based scatternet response is similar to the normal scatternet, since destination node is present in the network. If we compare Fig. 5.17 with 5.18, it is quite clear that when there is more than one route for the destination is present in the scatternet; the information can be reached to the destination with minimum delays.

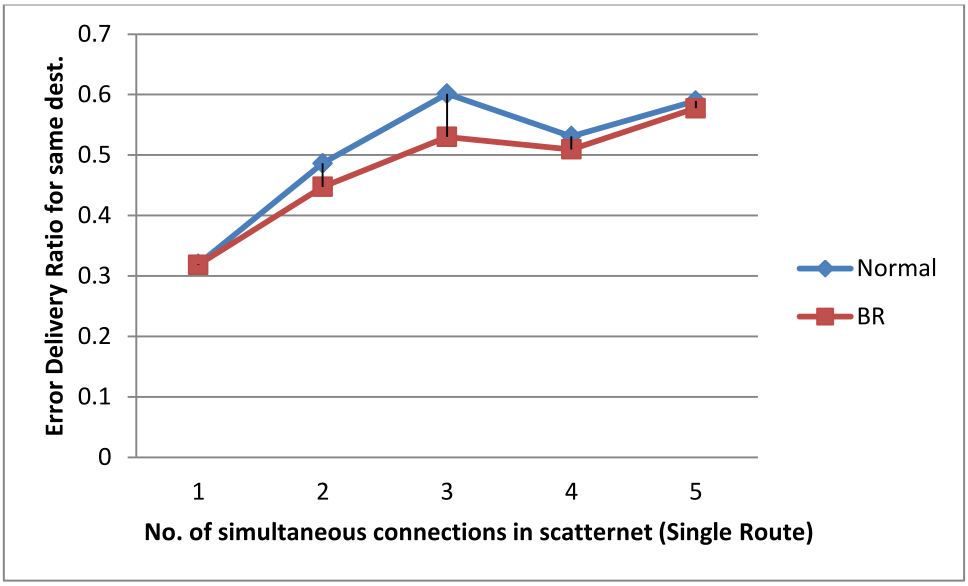


Figure 5.19 Packet error delivery ratio for the same destination with single route

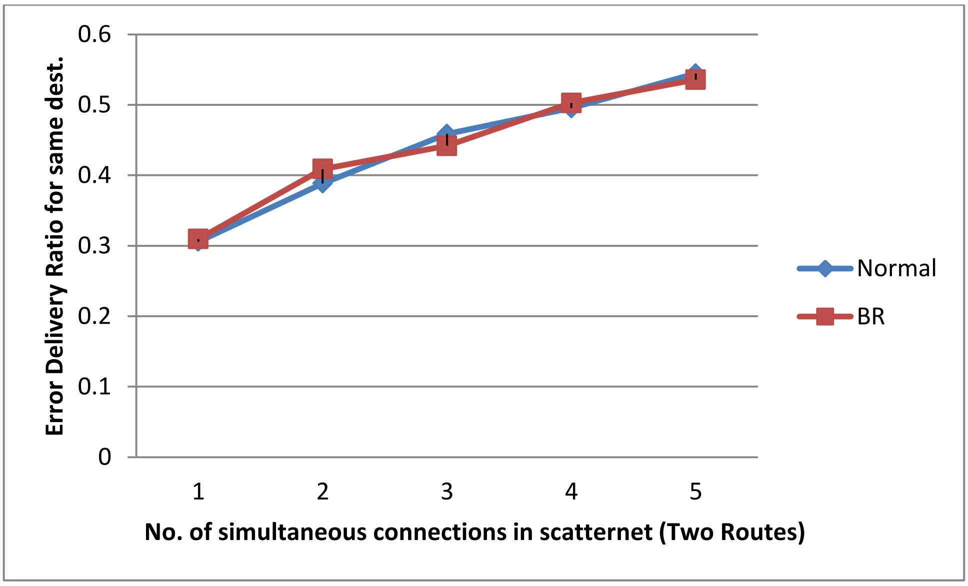


Figure 5.20 Packet delivery ratio for the same destination with two routes

Fig. 5.19 and Fig. 5.20 show the packet error delivery ratio for the same destination in scatternet in the presence of one and two routes respectively. Fig. 5.19 indicates that when there is only one connection the error is low, as the number of simultaneous connections increases in the scatternet the error starting to increase with variation. The reason behind this trend is that when there is only one connection in scatternet the maximum time is allocated to only one node as a result the node can transfer data at higher rates thus probability of error is low due to large amount of data can be transmitted. As number of simultaneous connection increases in the scatternet, master nodes of participating scatternet have to use the polling algorithm to equally distribute the time slots among its slaves as well as bridge nodes as a result each node will get a limited amount of time slots for data transmission, since nodes are now sending data with lower rates thus error delivery ratio is high. The BR-based scatternet shows almost the similar trends as shown by the normal scatternet with variation due to complex scheduling process in scatternet. Fig. 5.20 shows the better trend compare to Fig. 5.19 this is due to the fact that there are now two routes for the destination so less congestion in the network as a result better delivery ratio is achieved but still varying due to complex time scheduling in scatternet.

Fig. 5.21 & Fig. 5.22 show the typical energy consumption of same destination in presence of single and two routes respectively, with the increasing number of simultaneous connections from same source piconet to the same destination piconet. When there is only one active connection present between source piconet and destination piconet the energy consumption at destination node is highest due to high data rates. However when number of simultaneous connections starts to increase, the master node of destination piconet has to schedule the time slots for the equal share between other slave nodes in that piconet as a result the destination node gets the reduced chunk of time slot for transmission and reception of data, thus energy consumption is lower. The behaviour of BR-based scatternet is almost similar to the normal scatternet because the destination node is present in the scatternet. By comparing Fig. 5.21 & 5.22 it is quite evident that the energy consumption at destination node is much higher in the presence of two routes compare to the one route. This is because when there are two routes present between source and destination piconets, there will be less congestion in the scatternet as a result large amount of data can be transferred from the source to the destination as shown in Fig. 5.15 & Fig. 5.16, since destination node can now receive large amount of data this means that energy consumption at destination node will also be higher.

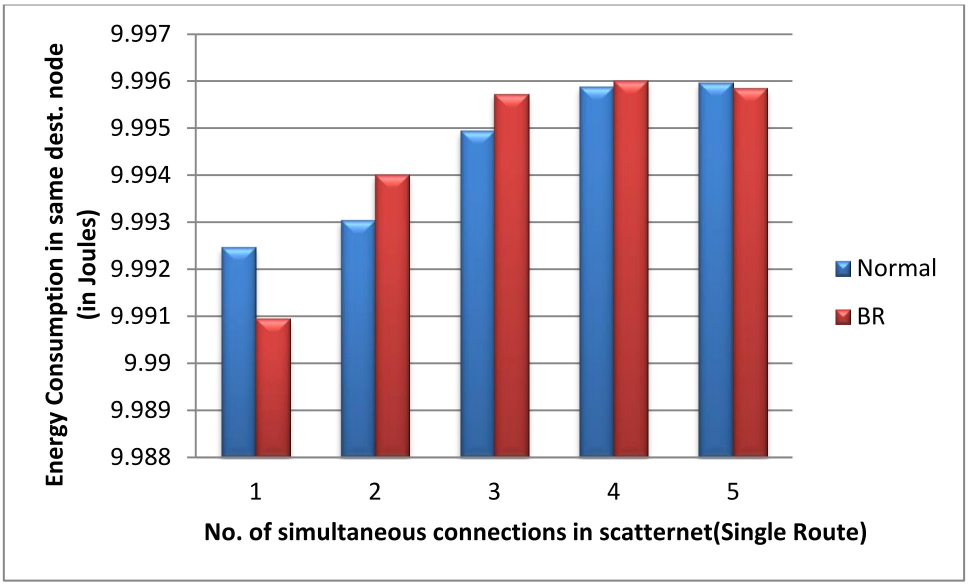


Figure 5.21 Energy consumption in scatternet with single route

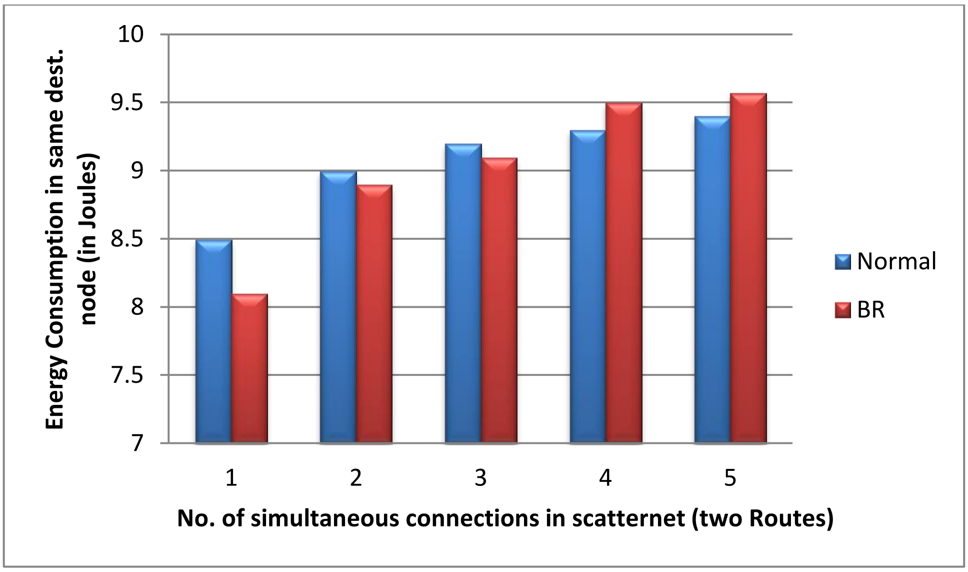


Figure 5. 22 Energy consumption in scatternet with two routes

So far experiments showed that BR-based scatternet acts almost similarly as normal scatternet as long as destination is present in the scatternet. In this experiment the aim is to check the behavior of BR algorithm, for this purpose the nodes selected as a destinations are not present in the scatternet. For BR-based scatternet, three different nodes such as node 20 in piconet '3', node 3 in piconet '1' and node 27 in piconet '4' have assigned social (popularity) ranks of 30, 25 and 20 respectively, whereas, all other nodes have given the default rank i.e. 1, as shown in fig 5.4. When the source nodes attempts to send the data and not able to find the destination then BR-algorithm comes into play and data will be sent to the node which is more popular than the current node, since routing protocol is AODV as a result each node in static scatternet knows that which node is the most popular node, therefore source node will target the highest (popular) ranked node. In order to check that nodes are indeed targeting the most popular node, after 50s of simulation the current highest node is removed from the network, as soon as node ‘20’ is removed from scatternet the nodes automatically start to target the second highest popular node i.e. node ‘3’ which is now become most popular node in the scatternet.

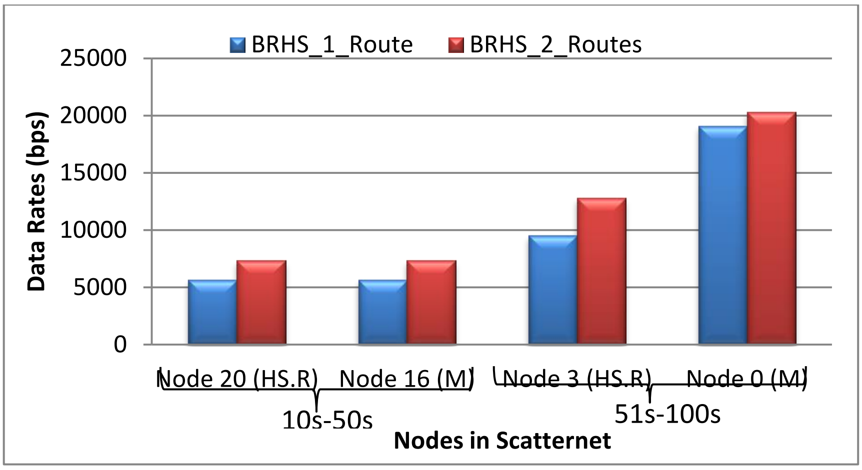


Figure 5.23 Data rates received at highest ranked node and master node in BR-based Scatternet

Fig. 5.23 shows the typical behaviour of BR-based scatternet in terms of data rates received at highest rank (HS.R) nodes and their respective master (M) nodes in the presence of one and two routes in scatternet. It is clearly shown in the figure that in order to reach at highest ranked nodes, if more than one route is present in scatternet; the data rates received are high. Figure 5.23 shows that data rates received at node ‘3’ and its respective master node is much higher compare to the node ‘20’ and its respective master node. The reason behind this behaviour is due to the fact that for this experiment the sources considered are present in piconet ‘2’, initially nodes are targeting the highest ranked node i.e. node ‘20’, that present in piconet ‘3’ which is far from piconet ‘2’. Whereas, node ‘3’ is present in piconet ‘1’, which is near to piconet ‘2’ (compare to the piconet ‘3’) and also piconet ‘1’ has other nodes which are transmitting data to piconet ‘4’, due to these extra transmissions in piconet ‘2’ master node (node 0) in that piconet shows the highest data rate response, whereas node ‘3’ is receiving messages for those nodes who are not present in the network when node ‘20’ is removed from the scatternet.

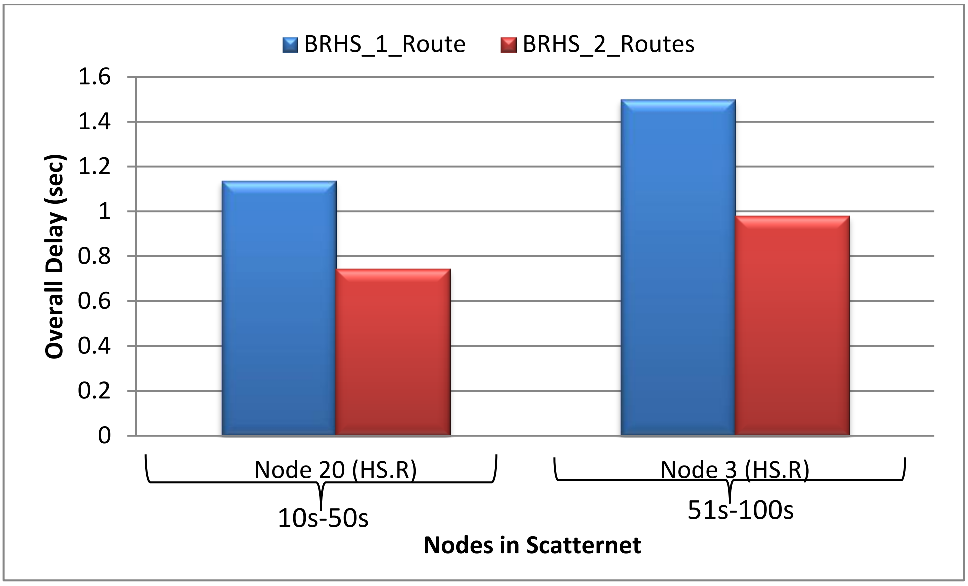


Figure 5.24 Delay response of highest ranked nodes in BR-based scatternet

Fig. 5.24 shows the delay response of the node ‘20’ and node ‘3’, which are 1st and 2nd highest (popular) ranked nodes, respectively. When 1st highest ranked node i.e. ‘20’ is removed from the scatternet , the unresolved queries for the destination nodes (not present in the network) is automatically send to the 2nd highest ranked node i.e. ‘3’(which is now become the highest popular node). Fig. 5.24 clearly shows that when more than one path is present in the network, the overall delay received at highest ranked nodes is starting to decrease.

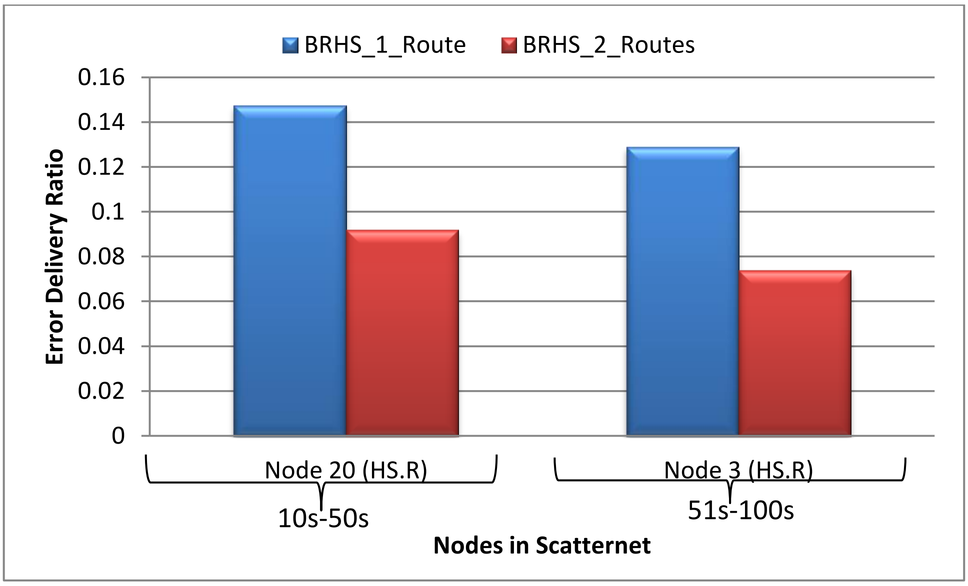


Figure 5.25 Error delivery ratio of highest ranked nodes in BR-based scatternet

Fig. 5.25 shows the packet error delivery ratio for highest (popular) ranked nodes. In both cases of node ‘20’ and node ‘3’, which are 1st and 2nd highest popular node in the scatternet respectively, the overall delivery ratio is improved in the presence of one and two paths for the highest ranked nodes. This again validates our findings that if more paths are available in the scatternet for the destination, better will be the overall packet delivery ratio.

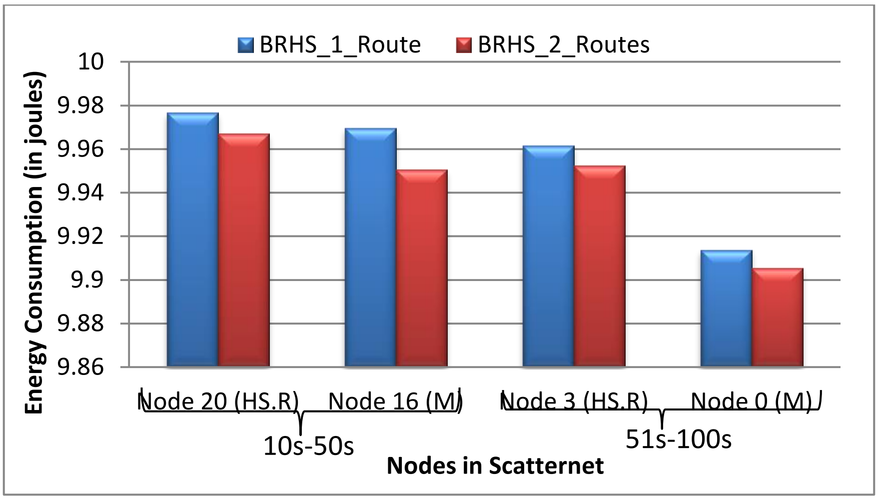


Figure 5.26 Energy consumption at highest ranked nodes and master nodes in BR-based Scatternet

Fig. 5.26 shows the energy consumption in 1st and 2nd highest ranked nodes and their respective master nodes, respectively. As found in our previous findings the master nodes will consumed more energy because it is responsible for its piconet, so here in this particular case not only the master node is handling the highest popular nodes but also the other nodes present in that piconet. This figure again proves that when more than one path is available in order to reach to the highest ranked nodes, the congestion in the scatternet becomes less as a result more data can be transmitted to these nodes, which will ultimately increase the energy utilization in participating nodes.

5.5.3) Results of dynamic scatternet in mobile source scenario

The experimental results presented in this section are based on experimental parameters and scenario discussed in section 5.4.3.1.

Fig. 5.27 shows the average data rates response at destination node which is static and present in piconet ‘2’, whereas source node is joining and leaving different piconets after specific period of time as depicted in Fig. 5.5. Fig. 5.27 shows variation in average data rates received at destination and there is time gap between those variations. The reason behind this behaviour is that when the source node leaves current piconet and joins another piconet this process will cause interruption in communication with destination, because source node has to join another piconet and has to handshake with new master node before resume communication again, thus requires 4-5 seconds to complete this process. The variation in average data rates received at destination node depends upon several factors such as how long node stayed at particular piconet, how many bridge or forwarding nodes were used in communication, how much busy a master node was in its piconet. Figure shows that destination node received high average data rate response when source node is connected to piconet ‘1’. The reason being that source node is connected with piconet ‘1’ for longer period of time as well as the source and destination piconets are directly connected. The gap shows leaving, joining and handshake time of source node among different piconets. The average data rate received at destination node is lowest when source node joined piconet ‘3’, reason being not only source node stayed there for short period of time but also between source and destination piconet there is another bridge piconet present, as a result data rates received at destination is lowest. Similarly, data rate response at destination node is fairly better when source node connected to the piconet ‘4’ and piconet ‘2’, respectively. Again variations in average data rate received at destination node is depend on the factors discussed earlier. In case of BR-algorithm, the response received at destination node is almost similar while source node is joining and leaving different piconets. This experiment also revealed that no matter where source node is in the scatternet, it will be able to transmit message to the destination provided if destination is present in that scatternet.

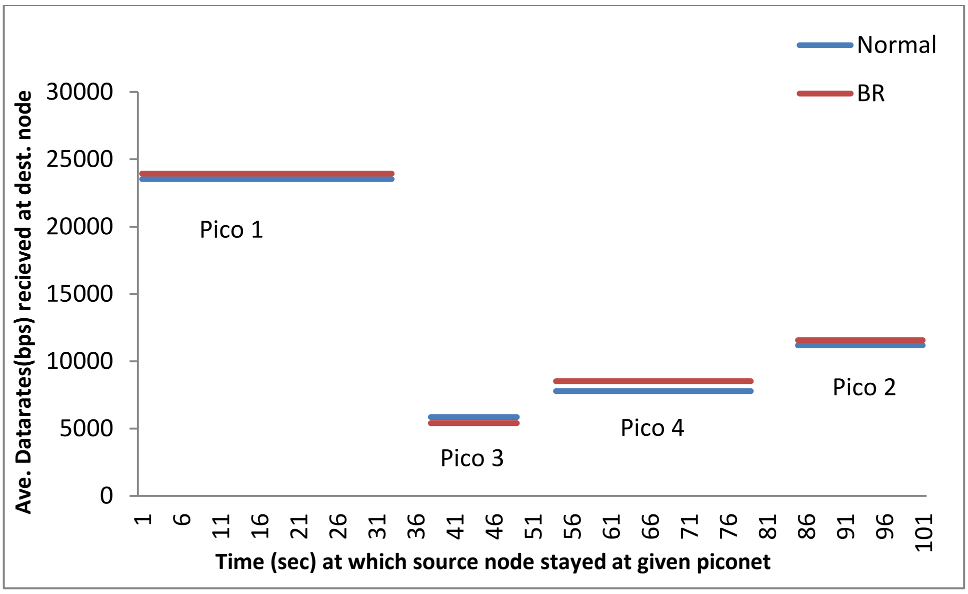


Figure 5.27 Ave. Data rate received at destination node whilst source node is mobile

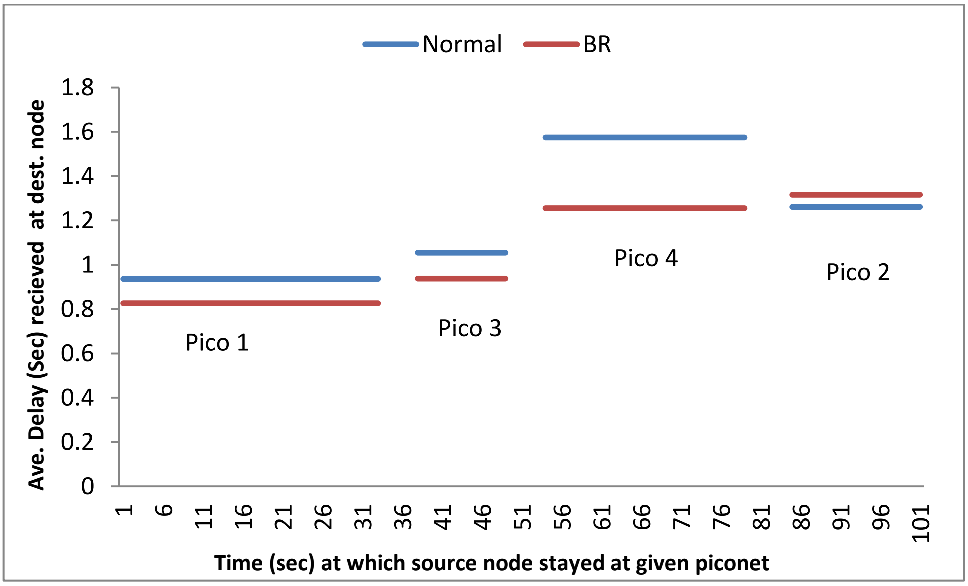


Figure 5.28 Ave. Delay rate received at destination node whilst source node is mobile

Figure 5.28 shows the average delay response between source node and destination node. Since source node is visiting different piconets, therefore delays received at destination node have variations. Time gaps in figure 5.28 indicate that there is no communication between source and destination node at that specific time period. This variation in delays is due to the fact that the communication is taking place in scatternet environment. This means that nodes can communicate with each other by forming different piconets and in a given piconet there can only be one master node and maximum of up to seven slave nodes. In order to make communication possible in a piconet, master node schedules the time slots and assigns each node a slice of time to allow them to send and receive messages. This means that a node can only communicate in its allocated time slot, so when more than one node is transmitting message in a piconet, it will increase the overall delay which will be experienced by all nodes present in that piconet. Similarly the node which is participating in two different piconets and acting as a bridge node has to wait for its assigned time slot in respective piconets to transmit messages to either of two piconets. This will also cause delays in the communication. If we compare normal scatternet communication with BR-based scatternet communication, even then we can find variation in delays because it depends upon at given communication time how many nodes are participating in the network, so if more nodes are participating in message transfer it will increase the overall delay as a result data received at the destination node has a varying delays. Overall, BR and normal scatternet showed the similar behaviour when source node is mobile and destination is static.

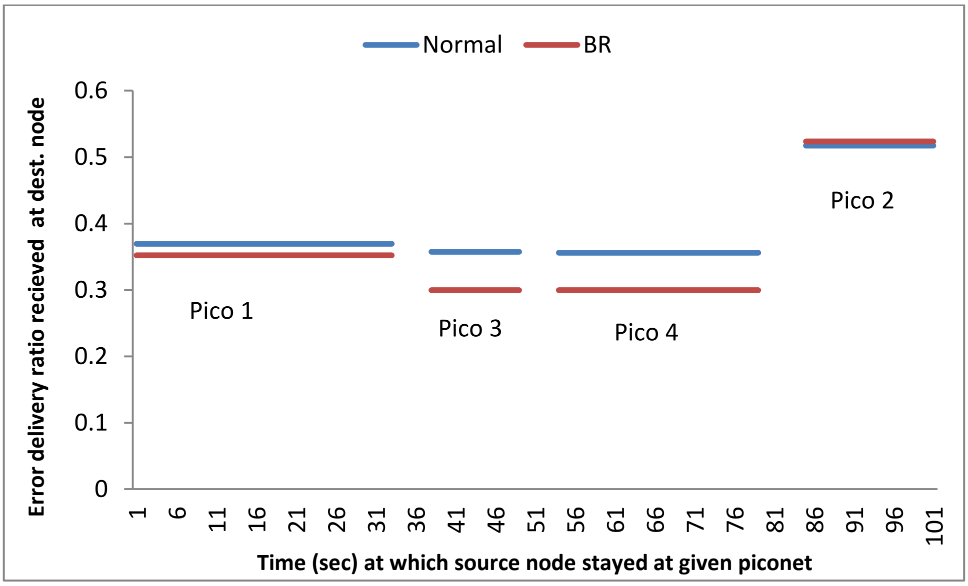


Figure 5.29 Error delivery ratio received at destination node whilst source node is mobile

Fig. 5.29 shows the average packet error delivery ratio for the same (static) destination in scatternet whereas source node is moving in different piconets. It is quite evident from the figure that no traffic is sent to the destination where gaps are present means source node is joining another piconet. The normal and BR scatternet showed almost similar behaviour except little variation in piconet ‘3’ and piconet ‘4’, which is acceptable range. The figure clearly indicates that despite of variation in average delivery ratio packets are still reaching to the destination while source node is visiting different piconets.

5.5.4) Results of dynamic scatternet in mobile destination scenario

The experimental results presented in this section are based on experimental parameters and scenario discussed in section 5.4.3.2.

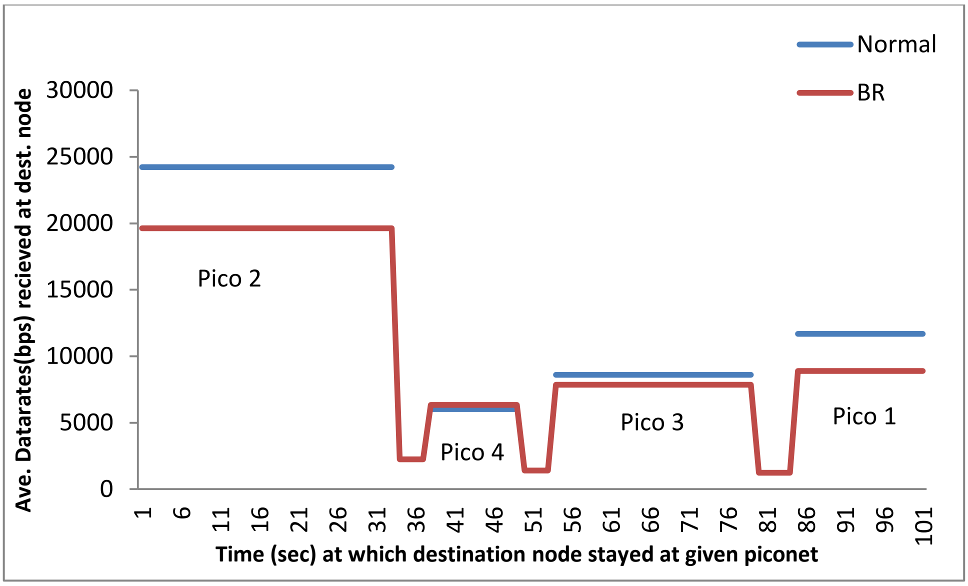


Figure 5.30 Data rate received at mobile destination node

Fig. 5.30 shows the average data rates response at mobile destination node, whereas source node is static and present in piconet ‘1’. The destination node joins and leaves different piconet after specific interval of time as depicted in figure 5.6. In case of normal scatternet communication environment when a node leaves and joins another piconet the communication between source and destination node gets interrupted and no message transfer takes place during handshake with the master node of new piconet. Again, there is variation in data rates received at destination node this is due to the reason that destination node is moving within scatternet, so location of destination is changing. Based on the distance from source node or the load on master nodes of participating nodes, the average data rate received at the destination node is varying. In case of BR-based scatternet, nodes have different popularity levels, the highest popular (ranked) node is present in piconet ‘4’ as shown in figure 5.6. In fig. 5.30 there is a sudden shift in data rate line when destination nodes leave a piconet until it joins the new piconet. These sudden shifts represent data rates received at most popular node. Since the BR algorithm is used here, so when source node is not able to find its destination, it will seek for the highest popular node and start sending packets to that node. When the destination node appears in another piconet, source node starts to send data back to the destination node again and also the most popular node which received data on behalf of destination node during the absence of destination node will also transmit that data (which it received from the source node) back to the destination node. In contrast with normal scatternet communication the BR allows source node to keep sending data even in the absence of destination node. But the situation get worse if a number of source nodes are not able to find their destination nodes, the all nodes will target the most popular node of the network, this situation can cause adverse effect on the network, because not only it will eats up the resources of most popular node but also the master node of that piconet where most popular node is present. If we closely look at the fig. 5.30 the average data rate bar is slightly lower for BR-based scatternet, because not only source node has to keep record of most popular node so requires little more processing time compare to the normal scatternet communications but also destination node is receiving data from two nodes now one from source node and other from most popular node. So, when there is more than one node transmitting data this means that master node has to use scheduling in order to distribute time slots among participating nodes as a result the behaviour of BR-algorithm is varying compare to the normal scatternet environment.

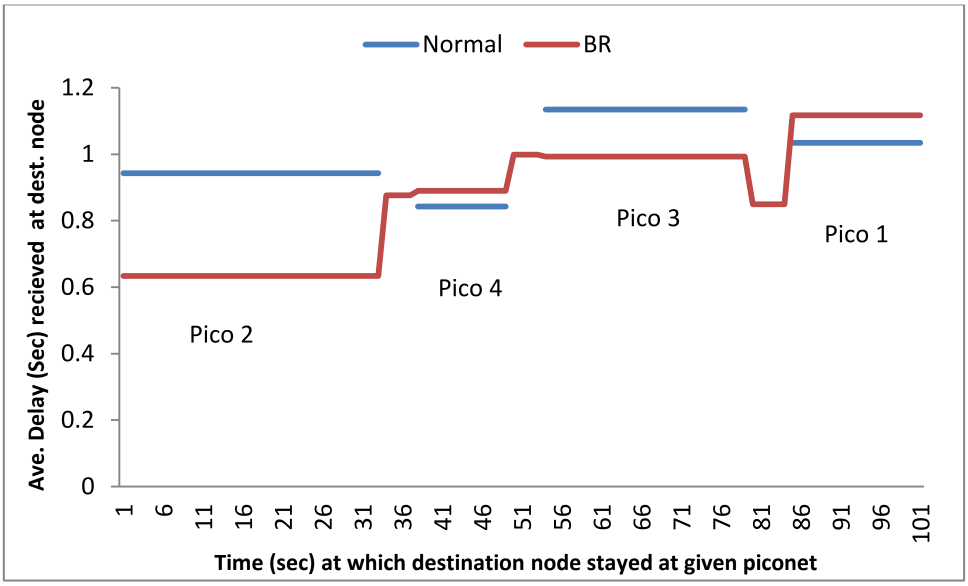


Figure 5.31 Delay received at mobile destination node

Figure 5.31 shows the average delay received at destination node during the communication from source (static) node to the destination (mobile) node. Again time gap represents that there is no communication taking place, because either destination node is in leaving or in join process with some piconets. In normal scatternet communication environment there is variation in delays received at destination nodes, this is due to the fact that destination node is joining and leaving different piconets, therefore location of destination node is keep changing with regards to the source node. So, if destination node is far from the source node or even if destination node is near to the source node but the piconet whom it joined with is very busy, this will create variations on average data rate received at destination node. In case of BR-based scatternet communication environment the variation received at destination node has similar causes as that of normal scatternet with the addition of most popular nodes. The sudden shifts in BR bar represents that delay received at most popular node, in this case it is located in piconet ‘4’. When destination node is not present in the scatternet (may be due to join or leaving process with piconets) the source node will start sending data to the most popular node. When destination node appears again in scatternet the source node will start sending data back to the destination node and also most popular node will send data to the destination node which it received during the absence of destination node. Since destination node is now receiving data from two different nodes it will cause more varying delay as shown in fig. 5.31.

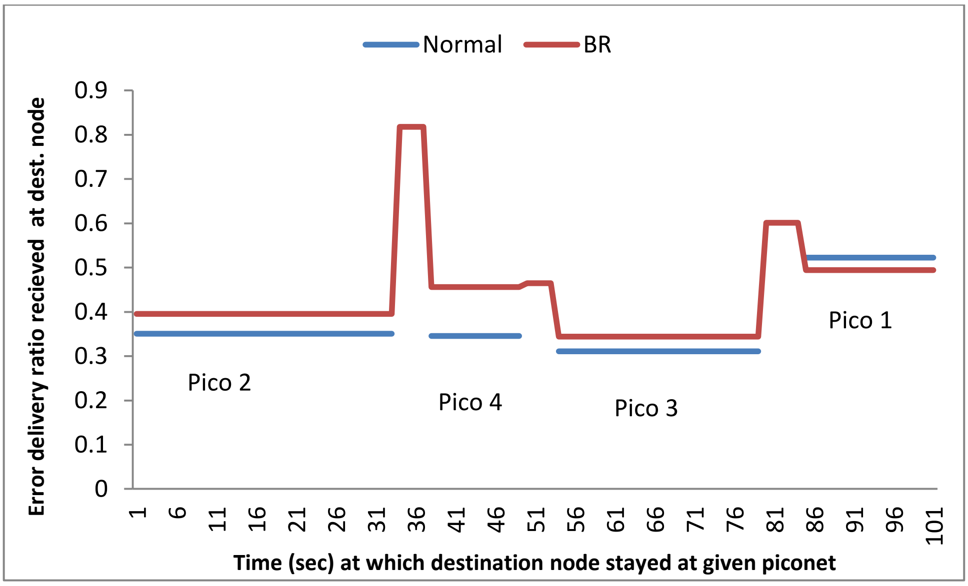


Figure 5.32 Error delivery ratio received at mobile destination node

Fig. 5.32 shows the average packet error delivery ratio for the same (mobile) destination whereas source node is static and present in piconet ‘1’.. In both type of scatternet environment the packet error delivery ratio is within reasonable range as shown in fig. 5.32. There are sudden shifts in BR bar this represents delivery ratio for most popular node, in this case present in piconet ‘4’. In the absence of destination node source node starts sending data to the most popular node; there is variation in delivery ratio for most popular node this is because when destination node leaves a piconet then source node start looking for most popular node which is present in piconet ‘4’, so long shifts represent time it takes for source node to locate most popular node. So, variation on delivery ratio depends upon the location of destination node present within the scatternet.

5.5.5) Results of dynamic scatternet in mobile H.R. scenario

The experimental results presented in this section are based on experimental parameters and scenario discussed in section 5.4.3.3.

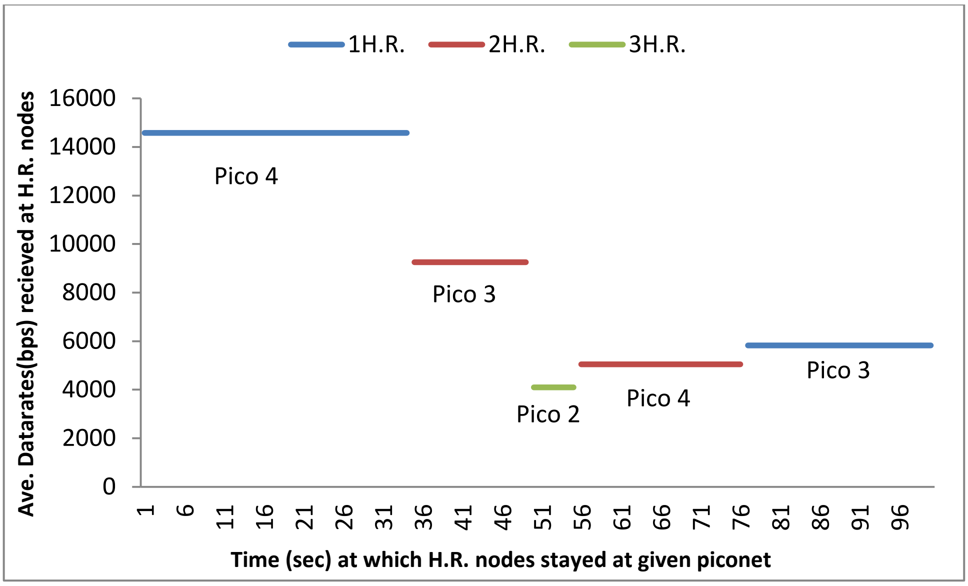


Figure 5.33 Data rate received at mobile HR nodes

Fig. 5.33 shows the average data rate received at highest ranked nodes. Initially 1HR which is the most popular node in scatternet is present in the piconet '4' as hown in figure 5.7. The source node that is present in piconet '1' starts sending data to the 1HR since it could not locate the destination node. After sometimes 1HR leaves the piconet '4' as a result 2HR now becomes the most popular node which is present in piconet '3' and now source node starts sending data to the 2HR. After certain period of time 2HR also leaves the piconet '3' and moves towards piconet '4' to join with. During the handshake process with the master node of piconet '4' 2HR is not present as far as source node is concerned, therefore source node start sending data to the 3HR, present in piconet '2'. As soon as 2HR appears in piconet '4' the source node start sending data to 2HR and at the same time 3HR also starts sending data to 2HR which it received during the absence of 2HR. Finally, when 1HR again joins the scatternet and appears at piconet '3'. The source node, 2HR and 3HR again start to send data to the 1HR, because now 1HR is the most popular node in the scatternet. In BR-based scatternet communication environment, if nodes couldn't locate destinations then they always seeks for the most popular node in scatternet and if a current most popular node finds another node whose ranking is higher than the current node, current popular node will also send data to the newest most popular node. Since HR nodes are leaving and joining different piconets, so average data rate received at HR nodes is varying, this is because physical location of HR nodes matters. If HR node is present far from the source node or it is present in a piconet which is very busy, in that case the data rates received at HR node may vary and this is what this experiment proves.

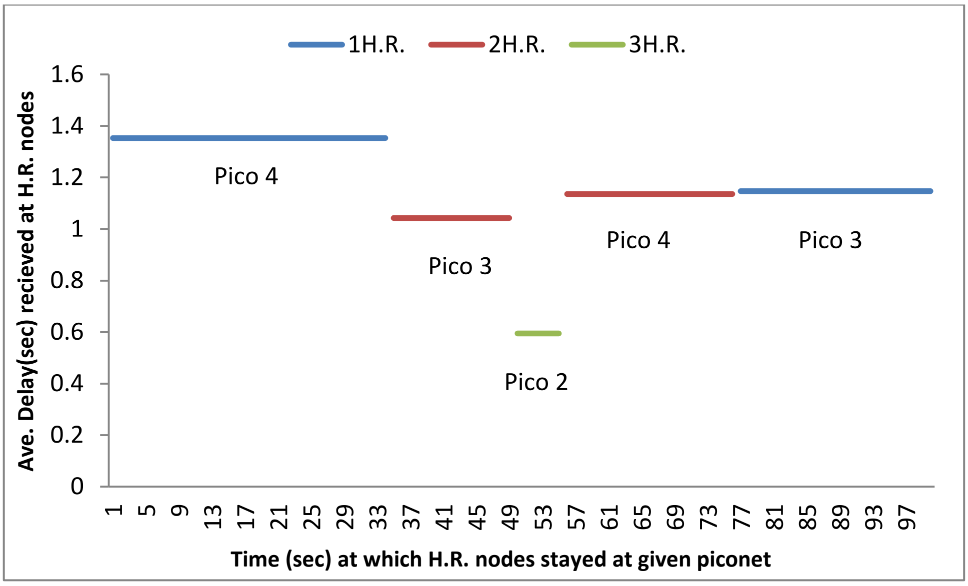


Figure 5.34 Delay received at mobile HR nodes

Fig. 5.34 shows the average delay received at HR nodes visiting in different piconets, whereas source node is static and present in piconet ‘1’. It is clear for the figure that delays received at highest ranked nodes have variation, this is simply because nodes appearing in different piconets have different communication conditions, a HR node might physically present in a distant location from source node or more nodes are present in its piconet for message transfer in that case master node of that piconet has to use scheduling to fairly distribute time slots thus causes extra delays. Overall, these factors create variations in message delivery and may differ at any given time. This experiment shows that if a delay is not of much concern then data can be reach to the HR nodes eventually and good for delay tolerant applications.

Fig. 5.35 shows the packet error delivery ratio at different HR nodes present in different piconets while source node is static and present in piconet ‘1’. Long bars and short bars that represent HR nodes defines that how long a HR node stayed in a particular piconet. Again there is variation in average packet error delivery ratio received at HR nodes due to the piconet conditions or the location of HR nodes from source node. It is clear from the figure that average packet error delivery ratio is within acceptable range and no matter where most popular node is present in the scatternet, the source node still manages to transfer data to the HR nodes.

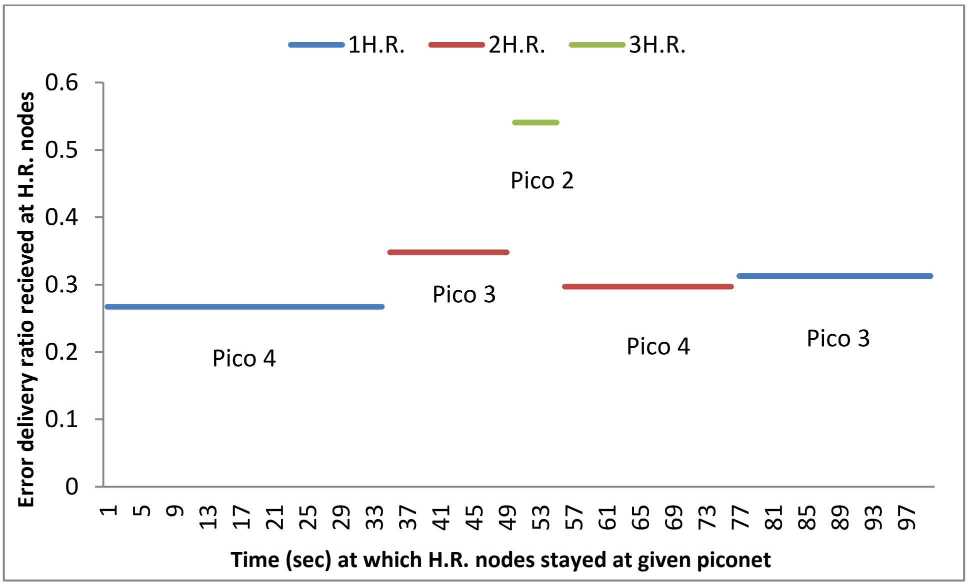


Figure 5.35 Error delivery ratio received at mobile HR nodes

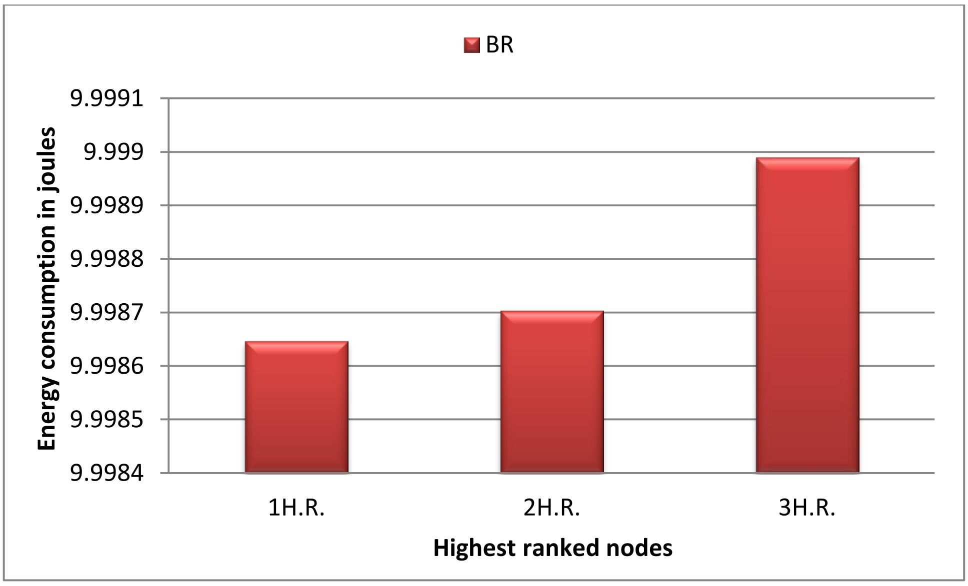


Figure 5.36 Energy Consumption at mobile HR nodes

Fig. 5.36 shows the average energy consumption in HR nodes during the whole simulation process. As it can be seen in Fig. 5.36 that 1HR node stayed alive for maximum period of time during the whole simulation process as a result source, 1HR and 2HR nodes have transferred their messages to 1HR, therefore energy consumption is maximum in 1HR. Whereas in case of 2HR the energy consumption is less than 1HR but more than 3HR because in the absence of 1HR, 2HR becomes the most popular node therefore source and 3HR node sending messages to the 2HR. Finally, energy consumption in 3HR is minimum this is because 3HR comes into play for very short period of time and only source node was sending data to 3HR in the absence of 2HR and 1HR. This experiment shows that in the absence of destinations, source nodes will always target the most popular node in the scatternet as a result the node which is most popular will naturally consume more energy.

5.5 Chapter Summary

This chapter presented the proof of concept study on ad-hoc routing algorithm such as AODV and opportunistic forwarding algorithm Bubble Rap (BR) in Bluetooth communication environment. Although, there is fundamental difference in these two types of algorithm. Ad-hoc algorithms are applicable in those areas where network is fully or partially in view. Whereas, opportunistic algorithms do not have any prior knowledge of network, it forward messages in the network based on the information it gets from encountering node. During this study, an idea is established that though these two algorithms are different in nature and applicable in specific environments, but they can complement each other. It is also learnt that efficient algorithms are required for the formation of scatternet which ultimately enhance the overall efficiency of network communication in Bluetooth networking environment. Experimental results show that by allowing opportunistic forwarding on top of traditional ad hoc network, now source nodes do not need to wait for direct encounters with potential forwarder or destination. In fact potential forwarders can be reached by using traditional ad hoc routing such as AODV even if they are multi-hop away in the scatternet.

Based on the findings presented in this chapter, next chapter presents a hybrid content forwarding technique by combining best of the two worlds. A node is able to switch its mode in ad hoc routing if network is fully or partially in view. Similarly, node can also switch to opportunistic forwarding mode if it finds single node in the network.

Chapter 6

HCF algorithm: Hybrid Content Forwarding Technique for Bluetooth Communication Environment

The previous chapter presented the proof of concept study that network reachability can be enhanced by combining traditional ad-hoc networks with emerging opportunistic networks. Since opportunistic networks are derived from ad-hoc networks, so they naturally complement each other. In previous chapter, it is learnt that by allowing opportunistic forwarding on top of traditional ad hoc networking enhance the capabilities of source nodes to reach out potential forwarders present multi-hop away in Bluetooth scatternets. Based on this learning this chapter presents a new forwarding technique by combing best of the two worlds in order to improve overall message delivery and communication cost. The idea is to rather waiting for direct encounters now source nodes can reach to potential forwarders that may present multi-hops away in scatternet by the help of traditional ad hoc routing.

6.1 Introduction

Mobile phones are so common these days, almost everyone carries one. Most of the mobile phone are now equipped with Bluetooth technology and each mobile phone has a unique Bluetooth ID in the world. This uniqueness makes a mobile phone ideal for ad-hoc communication in single and multi-hop environments. Bluetooth technology can be used as a cheap communication medium for information sharing (i.e. SMS or emails) or in situations where main telecom infrastructure is not available (i.e. disasters).

Many researchers [1, 2, 85] have proposed different algorithms for successful content dissemination in opportunistic networks and mainly these algorithms are simulated or experimented in Bluetooth communication environment. In opportunistic networks there is no prior knowledge of routes to the intended destinations. In order to forward messages in the network, nodes have to rely on local information or the information provided by the encountering node. Therefore, the primary task in these networks is to deliver content to the destinations with minimum communication cost. Epidemic [1] uses the concept of control broadcasting by not transmitting same packet twice to the same node. However, it still has a huge communication cost. On the other hand, Bubble Rap [2] is a social forwarding based algorithm addresses this issue by selecting forwarding node on the basis of popularity. Similarly, PeopleRank [85] inspired by Google's PageRank [86] measures the relative importance of the person within the network for ranking. By targeting higher PeopleRank nodes a significant reduction in communication cost is achieved. Almost all of these opportunistic algorithms considered one-to-one node communications, where nodes communicate using Bluetooth with only one encountering node at a time. However, one-to-one communication is not the only option; nodes can also communicate using single or multi-hop formation via bridge nodes in Bluetooth communication environment.

In Bluetooth, multi-hop communication can be realised by the formation of piconet or scatternets. Mobile ad-hoc networking (MANETs) protocols such as Ad hoc on Demand Distance Vector (AODV) or Destination-Sequenced Distance Vector (DSDV) are used in scatternets for route learning to the intended destinations. In piconet one master and seven slave nodes are allowed, master node has to play an important role as a central entity. In scatternet, more than eight nodes form multiple piconets and communicate each other via bridge node; bridge node has a key responsibility as a communicator among two piconets. Scheduling performance [56, 57] of the master node dictates the efficiency of a piconet. Whereas, not only scheduling performance of master node but also performance of bridge node does play an important role for overall efficiency of scatternet. Several bridge algorithms have been proposed [79, 80] for Bluetooth nodes acting as a bridge node in scatternet. In [16] Law et al proposed an efficient scatternet formation algorithm to minimise inter-piconet interference and avoid bottlenecks.

This chapter presents an approach where an effort is made to combine two different yet related ad-hoc communication approaches such as scatternet formation and social forwarding algorithms. For this purpose, the emphasis of this chapter is to make the routing and content dissemination more efficient by keeping Bluetooth protocol stack and human social relationship patterns in mind. Two well-known algorithms Bubble Rap (BR) [2] and scatternet formation algorithm [16] are combined to form a hybrid content forwarding (HCF) approach. This new hybrid approach is tested against BR in simple movement model (SMM) using NS-2 simulator. Experimental results have shown by combining these two approaches, the reachability of source nodes to its intended forwarders or destination nodes has greatly improved even if they are present multi-hop away from each other. Source nodes do not have to wait for direct encounters now they can reach beyond 10 meter range with the help of traditional ad hoc routing in scatternet. Graphs have shown that such hybrid approach not only increases the overall message delivery but significantly reduces the communication cost. Moreover, a significant decrease in delay is also observed.

The rest of the chapter organised as follows: Section 6.2 highlights the issues related to opportunistic forwarding. Section 6.3 details the concept of the hybrid content forwarding algorithm, also discusses the hybrid architecture. Section 6.4 gives the network modelling for simulation that includes simulation setup and scenario used. Section 6.5 provides the experimental results and discussion. Section 6.5 gives chapter summary.

6.2 Research Challenges

In opportunistic network, there is no prior knowledge of routes towards the destinations. The most of the state of the art algorithms address the efficiency of content delivery at destination nodes. However, these algorithms lack in addressing efficiency of communication cost and delay. This is mainly because nodes do not have partial or full view of the network; therefore they rely on some forwarding criteria. This forwarding criterion is used to compare suitability for the selection of potential forwarding node. For instance, in [2] author presented an algorithm known as Bubble Rap, where popularity is given to each node according to its social activeness. The idea is to transfer messages to more popular nodes; this will lead to the successful delivery of messages to its destination. Another interesting idea in [9] is that a person has a strong influence in a society if it has more connections such as diplomats who want more influence in a society but want fewer prices to pay in terms of cost i.e. making personal relationships or spending time. On the same lines, another concept known as lobby index [7] inspired from the diplomat dilemma i.e. a node has high lobby index if it has neighbours having at least equal or more neighbours then node itself in current communication environment. This means that a node having high lobby index can refer to those nodes which have high connections, thus reduces communication cost. Similarly, PeopleRank[86] measures the relative importance of the node in the network for node’s ranking. This concept is adopted from the Google’s PageRank [85], where it gives ranking to the websites for priority. By prioritizing nodes, PeopleRank significantly reduces the communication cost of the network.

In order to expand the capabilities of nodes to find its intended destinations with efficient message delivery, low communication cost and delay, this chapter presents a technique known as Hybrid Content Forwarding (HCF). In daily social life, same people tend to meet each other more often and most of them can be in group. For instance, group of people at home or in office, this type of social behaviour can be exploited for the means of efficient forwarding in opportunistic networks. Since there are chances of people to work together in a group or may apart but yet within 10m range as far as Bluetooth technology is concerned. This closeness can be exploited for the purpose of the formation of scatternets by using Bluetooth technology. Therefore, the idea behind HCF technique is to combine socially inspired algorithm such as Bubble Rap with traditional Ad hoc networks such as AODV on scatternets to increase capabilities of nodes in the network. The next section 6.3 will give the detailed insight of HCF algorithm.

6.3 Hybrid Content Forwarding Alogirthm

In human society, people form relationships such as family at home, colleagues in offices and friends, thus have specific patterns in their life. These patterns can be exploited for opportunistic content dissemination as presented in different social forwarding algorithms such as [2] where popularity is the criteria to choose forwarding nodes. Similarly, it is also possible that during visit to different places such as conferences or some gathering where people may come across with group of other people where they introduced with new friends. In terms of Bluetooth communication environment, such close gathering where many people present in a given area can be reach using scatternet formation of nodes such as presented in [16].

Figure 6.1 shows the typical architecture of hybrid protocol. In opportunistic network, a node may encounter one node or set of nodes while on the move. This means that when a node encounters only one node than it can rely on opportunistic forwarding technique. In case, when there are multiple nodes present in the area, rather than relying on one-to-one approach of opportunistic forwarding algorithm, a scatternet formation of nodes can be used. Scatternet can be formed to communicate with multiple nodes using MANETs protocols such as AODV or DSDV, within range or even out of range nodes. This kind of hybrid approach gives nodes to gain high reach and knowledge of the network as a result better message delivery with speed and low communication cost can be achieved. The hybrid approach sits on the top of scatternet formation algorithm as shown in figure 6.1, so any new and better scatternet formation algorithms come in future, will automatically enhance the efficiency of proposed approach.

Figure 6.1 HCF architecture

To understand the HCF approach, consider the scatternet formation in figure 6.2. The source node is present in Piconet ‘1’, destination node is initially present in piconet ‘2’ and the highest social ranked (popular) node present in piconet ‘4’. The destination node joins and leaves different piconets after specific interval of time as depicted in figure 6.2. Initially, source node is sending messages to the destination node in piconet ‘2’ using traditional MANET protocol such as AODV. After sometimes destination node leaves the network, at this point source node switch into opportunistic forwarding technique and relies on social forwarding algorithm and starts looking for most popular node in the network. By the help of AODV protocol it locates the most popular node such as node ‘26’ in piconet ‘4’ and starts forwarding the messages. When destination node re-joins piconet ‘4’ after sometimes, source node start sending messages directly to the destination node and during the absence of the destination node the data which is received by most popular node (node ‘26’) also sends data to the destination node. This kind of hybrid content forwarding approach gives following benefits:

- Hybrid content forwarding allows nodes to adopt one-to-one communication approach using opportunistically forwarding algorithm when very few distanced nodes are present in the network. However, when a group of nodes is present in the network, the hybrid content forwarding allows nodes to form scatternet and communicate each other using traditional ad-hoc protocols such as AODV.

- In absence of destination nodes, hybrid content forwarding allows source nodes to rely on opportunistic forwarding algorithm and send messages to most popular ones.
- With the help of scatternet, source and most popular nodes can reach to the destination nodes that may join anywhere in the scatternet using traditional MANETs protocols and vice versa.
- In Hybrid content forwarding nodes have the ability to reach those nodes which are beyond their transmission range with the help of bridge nodes in the network.
- In the absence of destination nodes, the source nodes forward messages to the most popular nodes. When destination node returns the source and most forwarding nodes start forwarding the messages to the destination. Due to this approach, a significant increase in message delivery ratio is expected.
- Low communication cost and fewer delays are expected because nodes can now directly reach to the intended destinations using traditional ad-hoc routing algorithms in scatternet environment.

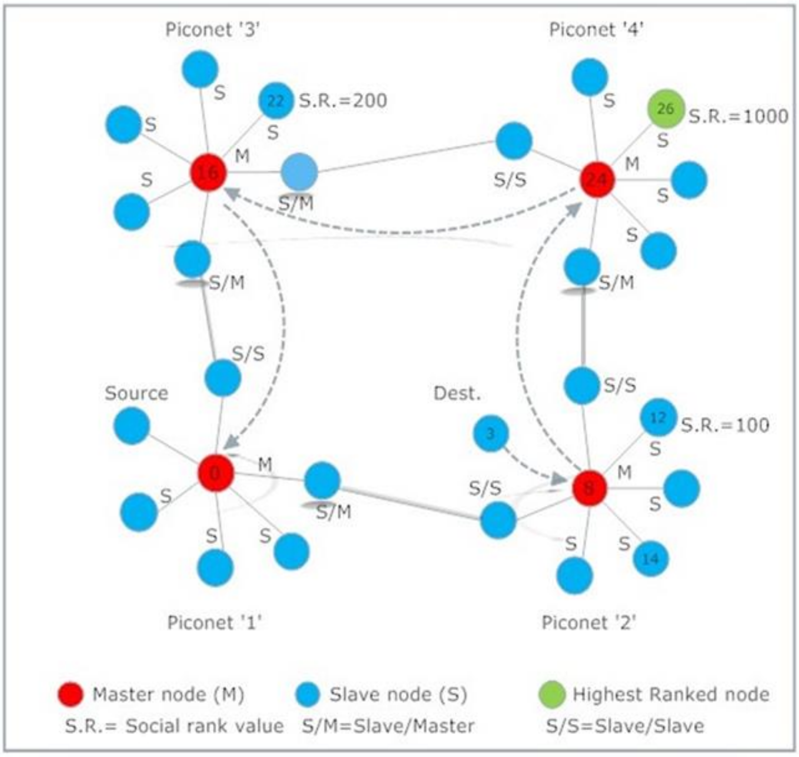


Figure 6. 2 Hybrid Content Forwarding (HCF)

6.4 Network Modelling

This section gives an overview of the simulation setup used for the purpose of this piece of research. Furthermore, this section also discusses scenario with simulation parameter used in these experiments.

6.4.1 Simulation Setup

To evaluate the HCF, a UCBT-Bluetooth extension for NS-2 simulator [20] is used for the simulation. UCBT-Bluetooth extension is specifically designed by keeping IEEE 802.15.1Bluetooth protocol stack in mind (for details please see section 5.4.1). The transmission range of each node is 10m and at 2Mbits/s data rate. Bubble Rap [2] is used as opportunistic forwarding algorithm, therefore, each node is allowed to update its popularity metric upon encounter with other nodes. The scatternet formation is achieved using the algorithm proposed in [16]. If more than one node is present in the communication range, nodes are allowed to form scatternets. Table 6.1 summarises the parameters used in this experiment.

Table 6.1 Simulation Settings

Parameters	**Value**
Total simulation time	28000s
No. of nodes	50
Area (range)	200x200m
Sub-Area (range)	30x30m
Transmit range	10 m
Node speed	1.5 m/s
Max. allowable slaves (per piconet)	07
Routing Protocol	AODV
Scheduling (or Polling) algorithm	PRR
Bridge Algorithm	TDRP
Packet Type	UDP
Packet Size	1400
Interval	0.015
Bluetooth Baseband packet type	DH5
Battery Life (initial)	10 J
Avg. energy consumption rate	2.5e-3 J
Min. Energy	0.1 J
Node Rank Recording (social popularity level)	Active
Probability of joining a group	0.5
Time to stay in a group	60-360s
No. of times each experiment run	30

6.4.2 Simple Movement Model (SMM) Scenario

In order to simulate HCF algorithm, a simple movement model (SMM) is devised to give the nodes hybrid environment. This hybrid simulation world has outer area boundary range of 200x200m and named as area ‘A’. Three sub-areas namely ‘B’, ‘C’ and ‘D’ are also defined, each having sub-boundary range of 30x30m inside area ‘A’, as shown in figure 6.3. In this hybrid environment, nodes are force to come closer in sub-areas within 10m range and stay there for some specific period of time to form scatternet to perform traditional ad hoc routing. Similarly, nodes that are moving outside sub-areas are distant from other nodes and are moving in random fashion therefore rely on opportunistic message forwarding. Each node has 50% probability of joining any of these groups and node can stay in a given sub-area between 60-360 seconds.

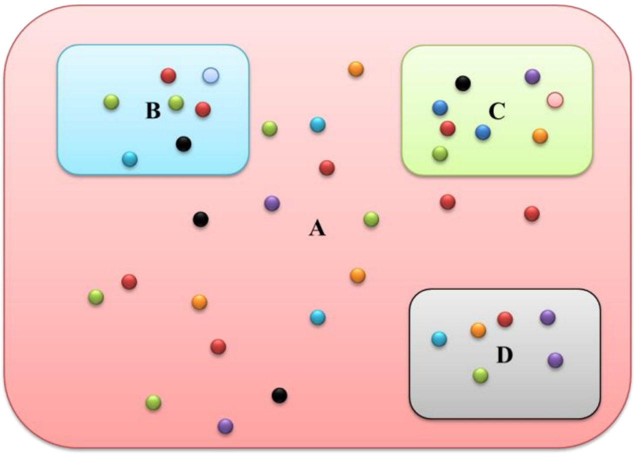


Figure 6. 3 Simple movement model

6.5 Results

Varying length of queue sizes are considered to measure the overall performance of algorithms. Queue size affects the overall performance of any routing algorithm, as this is natural that large queue size store more messages thus has less chance of message dropping. The algorithm performances are measured against three metrics: message delivery, communication cost and delays. Each of these graphs show two curves which represent the behaviour of BR and HCF algorithms. The X-axis of each graph represents varying queue sizes against which curves are plotted. Please refer to the section 6.4 network modelling for details of simulation scenario and parameters.

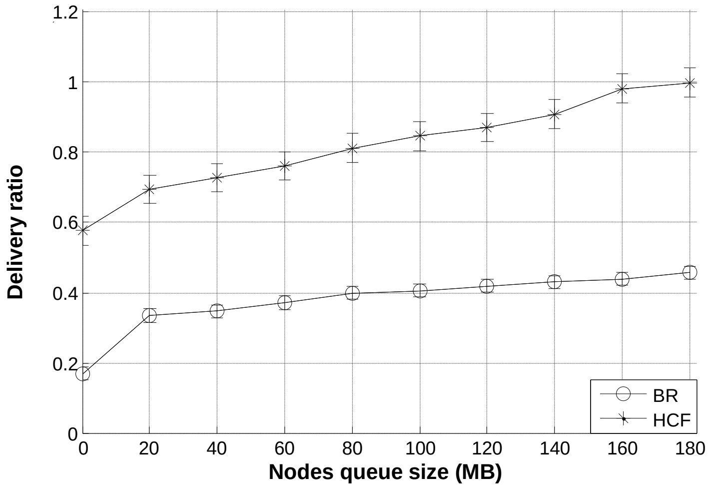


Figure 6. 4 Average delivery ratio at destinations

Figure 6.4 shows the normalised number of messages received at destination nodes in simple movement model. HCF shows remarkable results compare to just BR technique in terms of message delivery. In BR, message forwarding takes place only when more popular nodes encounter, whereas, HCF successfully adapts according to the network conditions. When group of nodes are close enough such as in communication range, HCF form scatternets and AODV routing is used for communication. However, BR comes into play, when isolated nodes encounters or destination nodes are not present in the network. In the absence of destination node, source node locates the most popular node in the network using AODV. After locating the most popular node, source node starts message transfer to the most popular node using BR concept. When destination node joins the scatternet, source node stops message transfer to the most popular node, instead resume messages directly to the destination node. However, during the absence of destination node, the messages stored at the most popular node are now being retransmitted to the destination node. Graphs in figure 4 show that the observations based on which HCF adapts network conditions are successful. This kind of hybrid approach indeed improves the overall message delivery ratio compare to just BR.

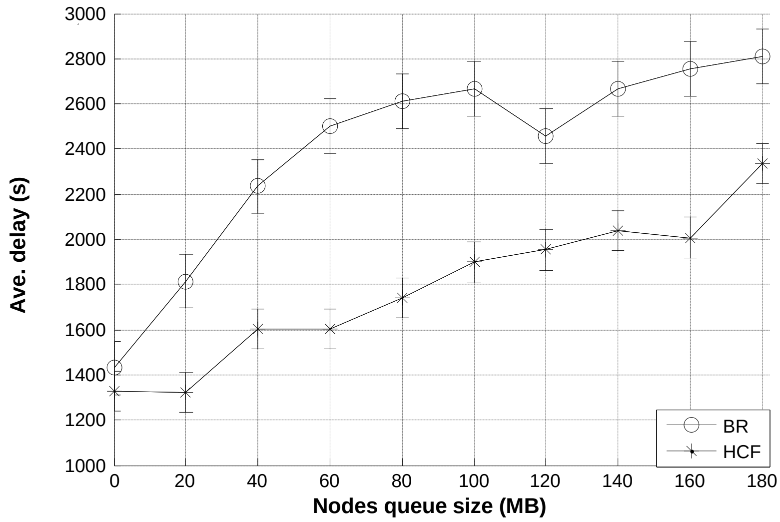


Figure 6. 5 Average message delays

Figure 6.5 shows the average delays experienced during the message transfer from source nodes to intended destinations. HCF shows fewer delays compare to BR. In BR, nodes keep messages until find more popular nodes. Whereas, HCF adapts according to network conditions, if destination node is present anywhere in the scatternet, the source node or popular nodes can reach to the destination node via bridge nodes using AODV algorithm. AODV rely on shortest path, therefore instead of waiting for direct encounter as in BR, HCF reach to those nodes as well which are beyond its communication range. This kind of hybrid communication decreases overall message delays in the network.

Figure 6.6 shows the normalised communications cost of the network and plotted its average. BR proves to be costly compare to HCF. BR keeps on forwarding the message to more popular nodes until finds destination node or time to live of message expires. In HCF, nodes do not necessarily have to forward message to every popular node it encounter, instead in scatternet formation nodes can locate the most popular node in the network using shortest routes learn from AODV algorithm and directly transmit messages to the popular nodes through bridge nodes.

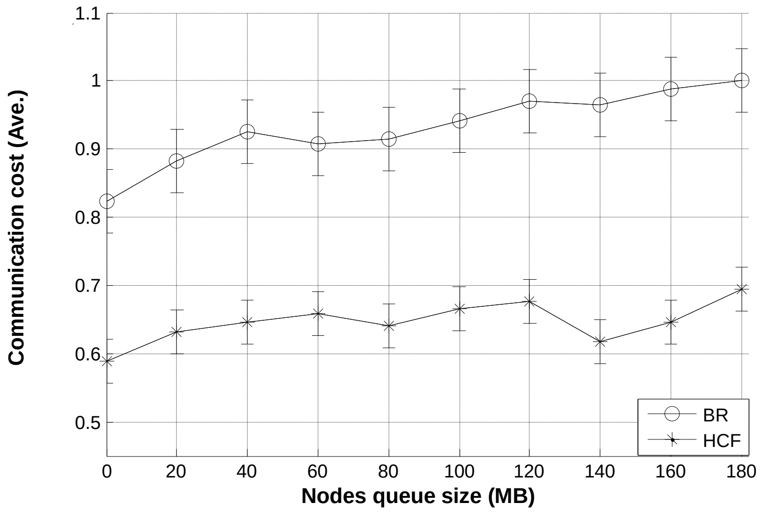


Figure 6.6 Overall network communication cost

6.5 Chapter Summary

In this chapter, a new algorithm Hybrid Content forwarding (HCF) is presented. The new algorithm combines the properties of socially inspired opportunistic forwarding technique with traditional mobile ad-hoc networks. It is quite evident from simulation results that the observations based on which hybrid content forwarding adapts network conditions turns out to be fruitful. HCF successfully forms scatternet formation when a set of nodes is present within range and also relies on opportunistic forwarding when one-to-one node encounter occurs.

Finally, experimental results confirmed that HCF proves to be far better algorithm than Bubble Rap (BR). Not only HCF out performed in terms of overall message delivery and communication cost but also significantly decreased the message delivery time. Use of traditional MANETs protocols with the combination of social forwarding algorithms certainly improves message delivery, delays and communication cost.

Chapter 7

Conclusion & Future Work

This thesis contains brief summary at the end of each chapter. However, this chapter concludes with the discussion of various research features presented in this thesis and summarizes overall accomplishments. Finally, gives the future direction of this thesis work.

7.1 Conclusion

This thesis presents various routing/forwarding techniques for message propagation in opportunistic networks. Specifically, investigates algorithms that exploit human social relationship analogies, location awareness and hybrid communication.

Chapter 2 discussed the state of the art routing/forwarding techniques in Opportunistic networks. In addition, chapter two explains the concept of delay tolerant networking (DTN) and its relevance in Opportunistic networks. It was revealed that indeed DTN concepts are the key ingredient for the successful communication in Opportunistic networks. In fact in Opportunistic network, nodes do not have prior knowledge of destination nodes, they rely information received from encountering nodes. In such kind of unpredictable communication environment, devices have to be delay tolerant. Innovations in wireless technologies i.e., Bluetooth and Wi-Fi enabled mobile devices have revealed the new horizons in communication arena and bring new ways to forward messages in Opportunistic networks. Researchers have presented different ways to make the message forwarding possible in infrastructure/less based Opportunistic communication environment. The literature review in this chapter has mainly focused on message forwarding techniques to improve the message delivery ratio in Opportunistic networks. There are some innovative and interesting techniques presented by some researcher that exploits human social behaviours to improve message directivity in Opportunistic network. Based on this literature review study, it was revealed that most of these techniques are focused on delivering the message to the recipient but during this process there is compromise in communication cost. In order to address the communication cost, new innovative and efficient techniques are required. Therefore, the prime objective and focus of this research is to devise new algorithms that not only improves the message delivery but at the same time can reduce communication cost.

Chapter 3 presented a socially inspired algorithm named as Enhanced Lobby Influence (ELI), where human social relationships pattern are exploited in order to achieve message directivity in Opportunistic networks. ELI is inspired from its predecessor Lobby Influence (LI) algorithm. The LI routing/forwarding technique exploits popularity or influence of nodes within the network. Although, LI technique improves message delivery significantly but still it lacks to address communication cost in the network. To address these issues, the ELI algorithm not only gives responsibility to un-popular nodes to share information with its popular neighbours but also allow nodes to keep track of nodes they met as final recipient, in order to improve communication cost and also keep the same level of message delivery efficiency as LI. If any midway node catches information to deliver for a recipient, which they recognize directly or has come across in any earlier information delivery as final recipient, should hold this information forwarding and retains it until they find final recipient themselves. Based on these observations, the new algorithm is tested in different scenarios i.e. in synthetic as well as in real mobility traces. The real mobility datasets contain the information gathered from experiments performed with real people and devices for certain period of time. The testing of new algorithm in real mobility traces helps us to learn the behaviour of new algorithm in real situations. However, real mobility traces have limitations in terms of resources such as number of nodes, movement models, device life, experiment duration time etc. Therefore, in order to further establish the robustness, the proposed algorithm is further tested in synthetic movement model. In synthetic movement model, there is more flexibility of changing experimental parameters to further gage the performance of proposed algorithm. Experimental results have shown that ELI not only outperformed in terms of message delivery but also significantly reduced the communication cost compared to its predecessor LI.

Chapter 4 presented another Opportunistic forwarding technique that addresses message delivery and communication cost. This technique relies on the location awareness of nodes in the network and named as Location-aware content forwarding (LOC). In LOC algorithm, nodes forward messages to those intermediate nodes which are close to the destination nodes and closeness of these nodes are determined through Global Positioning System (GPS) co-ordinates. The use of GPS co-ordinates has complete relevance with current mobile technology i.e. smart phones and therefore, motivation behind this LOC algorithm. Since, smart phones are intelligent devices and now being replaced with traditional mobile phones. A single smart phone is now equipped with multiple technologies such as Bluetooth, wireless LAN, GPS and GSM/LTE. Therefore, use of new mobile devices for the purpose of Opportunistic communication is more applicable than ever before. In LOC algorithm, source node is aware of its approximate destination node's position in the network by the help of Global Position System (GPS). The reference distance and direction values can be calculated from source to intended destinations by using direction vectors. The process of forwarding messages to intermediate nodes is very simple, forward messages to those nodes which have better direction and distance than reference values. By doing this, a great deal of message directivity is achieved and also significant amount of communication cost is reduced. In order to gage the performance, the new algorithm is tested in different scenarios i.e. in synthetic movement model and real mobility traces. The synthetic communication environment gave us the ability to test this algorithm in ideal situation. Similarly, real mobility traces gave us the idea about the performance of new technique in real situation. Experimental results have shown that observations based on which LOC algorithm performs message forwarding are proved to be true. The new algorithm achieved great deal of message directivity by targeting only those nodes which are closer to the intended destinations in terms of direction and distance and at the same time reduces the communication cost by not sending messages to irrelevant nodes. So far, this algorithm relied on GPS co-ordinates but it would be interesting to enhance it capabilities in indoor situations. This is completely doable by the help of mobile tower triangulation or by using wireless tethering.

Chapter 5 presented a proof of concept study to observe behaviours of ad-hoc and opportunistic algorithms in Bluetooth communication environment. Two different techniques ad-hoc routing algorithm such as AODV and opportunistic forwarding algorithm such as Bubble Rap are evaluated by keeping Bluetooth Communication stack in mind. These experiments were performed using NS-2 simulator, a very powerful simulator that simulates all layers of Bluetooth protocol stack. The experiment results have shown that the formation of piconet and scatternet can indeed achieve single and multi-hop communication in Bluetooth environment. Furthermore, opportunistic networks which are derived from ad-hoc networks naturally complement its ancestors. During this study, an idea is established that though these two algorithms are different in nature and applicable in specific environments, but in reality a node can find itself in any of these environments at any time. For instance, a node can encounter a group of nodes with in communication range, thus can establish piconet or scatternet and relies on traditional ad-hoc networks. Whereas, this is also true that a node may encounter just a single node in the network, in that case a node can rely on opportunistic forwarding. This study paved the way for next generation opportunistic forwarding techniques i.e. “combining best of the two worlds”.

Finally, chapter 6 presented hybrid model of two worlds such that by combining properties of Ad-hoc and Opportunistic communication. Since Opportunistic networks are derived from Ad-hoc networks, so naturally inherent properties from its predecessor and therefore complement each other. This natural amalgamation is the motivation behind this new technique, named as Hybrid content forwarding (HCF). The aim of HCF algorithm is to make the routing and content dissemination more efficient by keeping Bluetooth protocol stack and human social relationship patterns in mind. This algorithm adopts as per circumstances in the network. If single node is encountered, HCF relies on opportunistic forwarding. If multiple nodes are present with in communication range, this algorithm switches to traditional ad-hoc routing such as AODV and forms piconet or scatternet. The next challenge was to select the simulator that is powerful enough to simulate these two techniques. For this reason we selected NS-2, a very powerful free simulator that can operate in Bluetooth protocol stack. To simulate HCF technique, a simple movement model was devised where nodes are allowed to come closer in several places to form piconet or scatternet. Simulation results proved that the observations based on which hybrid content forwarding adapts network conditions turns out to be fruitful. HCF successfully forms scatternet formation when a set of nodes is present within range; also it relies on opportunistic forwarding when one-to-one node encounter occurs. Use of MANETs protocols in combination of social forwarding algorithms certainly improves message delivery, delays and communication cost.

In conclusion, the proposed algorithms employed various techniques to improve message delivery and communication cost in Opportunistic networks. In order to achieve better message directivity in network, these algorithms exploited human social relationship patterns, location awareness in network and combination of two breeds of algorithms. Furthermore, not only these algorithms were tested in various scenarios that contain different movement models in synthetic communication environment but also in real mobility dataset. Also, the new algorithms were compared with other well-known algorithms in various scenarios to measure the performance of proposed techniques.

Although, this research work has proposed various algorithms and techniques that are tested and verified with the help of rigorous simulation setup but still there is always room for improvements. For instance, real mobility datasets do not always contain enough node contact information that can truly justify the performance of an algorithm in a simulation. Therefore, selection of a real mobility datasets is a challenge. Mostly, in opportunistic networks, the primary focus of researchers is to address message delivery. However, communication cost and delay are the other factors of great importance that should be part of the research. In location aware algorithm, a GPS co-ordinates technique is proposed. However, GPS is helpful in outdoor activities, provided that there is no obstacle between device and satellites. In order to extend the capabilities indoor, mobile tower triangulation or WLAN tethering can be used.

7.2 Future Work

This thesis investigates routing/forwarding techniques by exploiting various aspects such as human social relationship analogies, location awareness and hybrid communication. This thesis just scratched the tip of the ice burg. There is a lot going on in the area of social sciences that can be used for the purpose of opportunistic forwarding. For instance, the way humans behave socially evolves every now and then, can be incorporated with technology to further enhanced opportunistic routing/forwarding techniques. Similarly, these days, most of the mobile phones are smart enough with computer like intelligence. Also, equip with multiple communication technologies such as Bluetooth, wireless LAN, GPRS and GSM. Different communication medium on single device have unlocked the new horizon of communication means. Modern mobile phones not only capable of using traditional way of communication via GSM or GPRS; but, also can use wireless LANs using access points where available. The use of multiple communications means to learn about the location of intended destinations in opportunistic networks, can further enhanced the ability of nodes to locate its interested nodes. Exploring this area has lot of potential for development of new enhanced location aware techniques. Finally, opportunistic communication can be used as an alternate communication means. In situation, such as disaster or wars where main telecommunication infrastructure is not working, opportunistic networking can be used as an alternate. In fact, devices such as mobile phone or laptop, if within range can use opportunistic networking for quick and cheap communication means.

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